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OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: October 23, 1978

Project Title: Combustion of Coal in an Opposed Gas-Particle Jet with Regenerative Pyrolysis

Project No: E-25-611 Green Card

Project Director: Dr. Pandeli Durbetaki

Sponsor: U. S. Department of Energy; Office of Procurement Operations; Washington, D. C. 20545

Agreement Period: From 9/1/78 Until 8/31/80 (Grant Period)

Type Agreement: Grant No. ~~ET-78-G-01-3305~~ EG22-78ET-13411

Amount: $50,000 DOE
4,607 GIT (E-25-345)
$54,607 Total

Reports Required: Summary of Research Progress; Annual Technical Report; Final Technical Report

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SPONSORED PROJECT TERMINATION

Date: 12/17/80

Project Title: Combustion of Coal in an Opposed Gas-Particle Jet with Regenerative Pyrolysis

Project No: E-25-611

Project Director: Dr. P. Durbetaki

Sponsor: U.S. Department of Energy

Effective Termination Date: 8/31/80 (R&D Period)

Clearance of Accounting Charges: 8/31/80

Grant/Contract Closeout Actions Remaining:

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E-25-611

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
Atlanta, GA 30332

Six-Month Progress Report No. 1

COMBUSTION OF COAL IN AN OPPOSED GAS-PARTICLE JET WITH REGENERATIVE PYROLYSIS

by
P. Durbetaki
Professor
and
Principal Investigator

Prepared for
Office of University Activities
U.S. Department of Energy
Grant No. ET-78-G-01-3305

23 February 1979

1. Objective

The burning of coal particles is the combined effect of the interlinked processes of pyrolysis, ignition and combustion of the volatiles and char. Efficient burning of these particles requires an understanding of the various processes and their respective influence on the entire cycle. The overall objective of this investigation is to study the effect of regenerative pyrolysis on the combustion of coal. A flat flame burner with an opposed gas-particle jet will be used in these studies. The work will be coupled with measurements using a Lower Ignition Temperature and Concentration Apparatus. The latter will provide variable heating rates for rapid pyrolysis to generate pyrolysis gases and use these gases for characterization. The three tasks of the experimental work are: (i) ignition of pyrolyzates, coal and char, (ii) rapid pyrolysis of coal, and (iii) combustion of coal and char.

2. Overview of Progress

The effective starting date for this grant is specified as 1 September 1978 and official notification was received by the Principal Investigator around the middle of September. Consequently, the work on this program was initiated during the first week in October 1978. Mr. Vinton L. Wolfe, Jr.

who is currently completing his requirements for the M.S. in M.E. degree and continuing for his doctoral studies joined the program as a Graduate Research Assistant.

Two coals were selected for the studies. A sample of bituminous coal was obtained from Georgia Power Company, and it was prepared and size graded. The coal was first dried and then using screens it was graded into various size ranges. A sample of brown coal (lignite) was obtained from the U.S. Bureau of Mines, Liaison Office, North Dakota. This coal will also be dried and size graded in the near future. An overview of the progress on the three tasks follows.

2.1. Ignition of Pyrolyzates, Coal and Char. The flat flame burner with the opposed gas-particle jet to be used for these studies was modified and all flow measuring instrumentation and temperature probes have been assembled. Characterization of the flat-flame burner has been initiated to establish the range of usable equivalence ratios for the air-methane mixture and flow rates for the carrier gas flowing through the jet tube. At the same time temperature profiles in the reaction zone and in the jet tube are being established for each set of conditions. A preliminary check of the particle feed system indicated that it will not provide a uniform and well controlled feed of particles. Consequently, it was decided to make a substantial modification on the particle feed system. A preliminary design on the modification of the particle feed system has been done and manufacture of the needed components will be carried out in the near future. This task is only about a month behind schedule and it is partially due to the later start of the program and the need for a more substantial modification in the powder feed system.

2.2. Rapid Pyrolysis of Coal. The rapid pyrolysis apparatus, LITACA, has been modified and preliminary measurements carried out. The reaction cell has been used in the measurements of minimum self-ignition temperature of gaseous fuel. Fuels used for these preliminary measurements have been commercial propane and technical grade methane. A check on the instrumentation and establishement of testing procedures were accomplished during these group of tests. The system is now being prepared to carry out preliminary pyrolysis tests with coal. This task is only about a month behind schedule and it is primarily due to the later start of the program.

2.3. Combustion of Coal and Char. This task is not scheduled to start until some later time in the program.

E-25-611

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
Atlanta, GA 30332

Six-Month Progress Report No. 2

COMBUSTION OF COAL IN AN OPPOSED GAS-PARTICLE JET WITH REGENERATIVE PYROLYSIS

by
P. Durbetaki
Professor
and
Principal Investigator

Prepared for
Office of University Activities
U.S. Department of Energy
Grant No. ET-78-G-01-3305

23 February 1980

1. Objective

The burning of coal particles is the combined effect of the interlinked processes of pyrolysis, ignition and combustion of the volatiles and char. Efficient burning of these particles requires an understanding of the various processes and their respective influence on the entire cycle. The overall objective of this investigation is to study the effect of regenerative pyrolysis on the combustion of coal. The specific objectives for the current research program are (i) to establish an operating system with regenerative pyrolysis, (ii) to identify the primary parameters which effect the ignition and combustion of particles in this system, (iii) to identify measurements which are needed and techniques to be developed for these measurements, and (iv) to establish a preliminary basis for a modeling analysis. The three tasks of the experimental work are: (i) ignition of pyrolyzates, coal and char, (ii) rapid pyrolysis of coal, and (iii) combustion of coal and char.

2. Overview of Progress

Mr. Vinton L. Wolfe, Jr. who completed his requirements for the M.S. in M.E. degree and currently is continuing his doctoral studies joined the program as a Graduate Research Assistant in October 1978. Two coals were selected for the studies. A sample of bituminous coal was obtained from Georgia Power Company. A sample of lignite (brown coal) was obtained from the U.S. Bureau of Mines, Liaison Office, North Dakota. Both coals have been size graded into seven groups. A flat flame burner with an opposed gas-particle jet has been used in the regenerative pyrolysis studies. The work has been coupled with measurements using a Lower Ignition Temperature and Concentration Apparatus. The latter provides variable heating rates for rapid pyrolysis to generate pyrolysis gases and use these gases for characterization. An overview of the progress on the three tasks follows.

2.1. Ignition of Pyrolyzates, Coal and Char. The flat flame burner used for these studies was modified and all flow measuring instrumentation and temperature probes assembled. Characterization of the flat-flame burner has been carried out to establish the range of usable equivalence ratios for the air-methane mixture and flow rates for the carrier gas flowing through the jet tube. A fluidized bed system coupled with an aspirator has been designed and built as a particle feed system for small particles and low particle flow rates. Using a 1.27 cm diameter jet it was found that of the seven groups of particles only the smallest two groups can be used in these studies without particle accummulation on the top of the burner. Temperature profiles have been measured in the reaction zone and in the jet tube. A computer program has been developed to transfer the temperature profiles into isotherms. Measurements for this task are currently being continued.

2.2. Rapid Pyrolysis of Coal. The rapid pyrolysis apparatus, LITACA, has been modified and measurements have been carried out using coal. A complete set of experiments were carried out with bituminous coal using heating rates ranging from 1000°C/min to 6000°C/min and initial atmospheres of nitrogen and air. The reaction cell has been used in the measurements of minimum self-ignition temperature of the gaseous fuel as a function of mass fraction of the fuel in a mixture with air. Apparent molecular weights were also determined for the generated fuel. These studies are now being extended to lignite coal.

2.3. Combustion of Coal and Char. Preliminary studies in the self-sustaining combustion mode of coal particles in the regenerative pyrolysis system has shown the requirement of a high flow rate of particles. These studies are now being continued.

E-25-611

ANNUAL REPORT

COMBUSTION OF COAL IN AN OPPOSED GAS–PARTICLE JET WITH REGENERATIVE PYROLYSIS

By

P. Durbetaki
Professor
and
Principal Investigator

V. L. Wolfe, Jr.
Graduate Research Assistant

Prepared for

Office of University Activities
U. S. Department of Energy
DOE Grant No. ET–78–G–01–3305

31 August 1979

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL ENGINEERING
ATLANTA, GEORGIA 30332

1979

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COMBUSTION OF COAL IN AN OPPOSED GAS-PARTICLE JET WITH REGENERATIVE PYROLYSIS

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DOE Grant No. ET-78-G-01-3305

31 August 1979

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
Atlanta, Georgia 30332

COMBUSTION OF COAL IN AN OPPOSED GAS-PARTICLE JET WITH REGENERATIVE PYROLYSIS

Annual Report

By

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and
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31 August 1979

Prepared for
Office of University Activities
U.S. Department of Energy
DOE Grant No. ET-78-G-01-3305

P. Durbetaki, Principal Investigator

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ACKNOWLEDGEMENT

The work presented in this report was carried out with the support of the Department of Energy (DOE) Grant No. ET-78-G-01-3305. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE.

ABSTRACT

The burning of coal particles is the combined effect of the interlinked processes of pyrolysis, ignition and combustion of the volatiles and char. Efficient burning of these particles requires an understanding of the various processes and their respective influence on the entire cycle. The proposed research study is an effort in that direction. The overall objective of this investigation is to study the effect of regenerative pyrolysis on the combustion of coal. The specific objectives for the current research program are: (i) to establish an operating system with regenerative pyrolysis, (ii) to identify the primary parameters which effect the ignition and combustion of the particles in this system, (iii) to identify measurements which are needed and techniques to be developed for these measurements, and (iv) to establish a preliminary basis for a modeling analysis. A flat flame burner with an opposed gas-particle jet has been used in these studies. Preliminary measurements indicate that pyrolysis gas ignition is dependent on the particle flow rate, carrier gas velocity and carrier gas composition. The work is coupled with measurements using a Lower Ignition Temperature and Concentration Apparatus. This apparatus provides variable heating rates for rapid pyrolysis to generate pyrolysis gases and use these gases for characterization. The effect of the heating rate during pyrolysis, for the fuel and heating rates tested, was found to be a broadening of the flammability limits and the reduction of the apparent molecular weight of the gases, with increasing heating rate.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

When pulverized coal particles are injected into a hot oxidizing atmosphere the particles undergo rapid heating with some volatile loss, ignition and combustion of the volatiles and char. The characteristics of each of these processes vary quite significantly depending upon the size distribution of the coal particles and corresponding environment. Efficient combustion of the entire coal particle requires an optimal execution of the pyrolysis, ignition and combustion processes.

Although ignition and combustion behavior of coal particles have been investigated extensively in the U.S. and abroad [1-12] many aspects of these processes have been determined only qualitatively [7-13]. Reviews on the qualitative and quantitative aspects of this problem can be found in four papers published during the last decade [7,13-15].

A century long held notion was that the ignition of coal always occurs in the gas phase. Presently, it is still common to relate the ignition characteristics of coal on the flammability of the volatile gas of coal [16]. Howard and Essenhigh [3,17] were the first to disprove experimentally such an occurrence for all coal particles and later by Thomas et al. [18], Bandyopadhyay and Bhaduri [19], and Annamalai and Durbetaki [11,20]. Thus there is evidence that for partially pyrolysing material like coal ignition occurs both at the surface and in the gas phase. The mode of ignition depends upon particle size, volatile content, ambient oxygen concentration and pressure.

The existence of volatiles in the fuel and their effect during the combustion process is very important. With cellulosic material it has been observed that the heating rate during pyrolysis has a pronounced effect on the composition and ignition characteristics of the pyrolysis gases [21]. In atmospheric combustion of coal the pyrolysis generally takes about ten percent of the total combustion time. Variables such as pressure, particle size, particle dispersion and rate of heating are important in establishing the amounts of volatile yield during pyrolysis [22-25].

Another interesting result in the burning of carbon at low pressure is that the reaction rate shows a peak at some surface temperature of the carbon/char [26] and this is true even at very low pressures [27]. The results point out that the increasing pressure has the tendency to shift the peak reaction rate towards a higher temperature [10,12]. Such a shift in the temperature is very desirable for some power generating systems.

Howard and Essenhigh [3] have shown that there exists a certain critical particle size for the coal particles where the flame just anchors on the particle surface. This fact leads to the conclusion that for a particle size below this critical value there could be no gas phase combustion [3,16]. Recently Annamalai and Durbetaki [28] have obtained critical sizes for the gas phase extinction of flames for coal particles and hydrocarbon droplets by extending the theory of Spalding for opposed jet diffusion flame. These critical sizes give only a sufficient condition for extinction, once a flame is established.

The above discussion and summary of past work makes it evident that there exist uncertainties with regard to the ignition phase of coal particles, pyrolysis, combustion of char and extinction of burning coal particles. The proposed study will be an initial effort in providing some understanding of the processes involved during various stages of the combustion of coal particles and their interaction to provide efficient burning of these particles.

1.2. Relevance

Although ignition and combustion behavior of coal particles have been investigated extensively in the U.S. and abroad, many aspects of these processes have been determined only qualitatively. The expanding use of coal requires design of equipment to process and introduce the fuel in the combustion systems. In some instances there is also a need to modify existing equipment. In all these cases it is important that the design is a result of an understanding of how the various processes in the burning of coal particles interact to achieve an optimum operation of the system. The proposed method of regenerative pyrolysis is expected to provide an enhancement in the burning of coal particles. Establishing the operating conditions and the values of those variables which will bring about this enhancement are important. It is also expected that the regenerative pyrolysis process will enable the system to operate at lower temperatures and consequently reduce the production of oxides of nitrogen. Consequently, these studies although preliminary, are relevant both from an economical and an environmental point of view.

1.3. Current Program Objectives

The burning of coal particles is the combined effect of the interlinked processes of pyrolysis, ignition and combustion of the volatiles and char. Efficient burning of these particles requires an understanding of the various processes and their respective influence on the entire cycle. The overall objective of this investigation is to study the effect of regenerative pyrolysis on the combustion of coal. The specific objectives for the current research program are: (i) to establish an operating system with regenerative pyrolysis, (ii) to identify the primary parameters which effect the ignition and combustion of the particles in this system, (iii) to identify measurements which are needed and techniques to be developed for these measurements, and (iv) to establish a preliminary basis for a modeling analysis. A flat flame burner with an opposed gas-particle jet will be used in these studies. The work will be coupled with measurements using a Lower Ignition Temperature and Concentration Apparatus. The latter will provide variable heating rates for rapid pyrolysis to generate pyrolysis gases and use these gases for characterization.

The current program has been divided into four tasks:

Task 1. Ignition of Pyrolyzates, Coal and Char

Task 2. Rapid Pyrolysis of Coal

Task 3. Combustion of Coal and Char

Task 4. Preliminary Modeling Analysis

2. IGNITION OF PYROLYZATES, COAL AND CHAR

2.1. Purpose

The purpose of this task is to determine the effect of preheating on the ignition of coal and char particles. The flat flame burner with an opposed gas-particle jet will be used for these studies. Variables to be considered are the type of fuel, particle size, level of preheating, composition of carrier gas, temperature field and composition of oxidizing atmosphere.

2.2. Achievements

Two coals were selected for the studies. A sample of bituminous coal was obtained from Georgia Power Company. A sample of lignite (brown coal) was obtained from the U.S. Bureau of Mines, Liaison Office, North Dakota. Both coals were size graded into seven groups. The flat flame burner with the opposed gas-particle jet to be used for this task was modified and all flow measuring instrumentation and temperature probes were assembled.

Two particle feed systems were designed and built. One a screw type particle feeder provides high particle flow rates and can be used in association with large particles. The second particle feeder utilizes a fluidized bed and aspirator combination. This particle feed system provides low particle flow rates and it is best suitable for use with the small particles.

Burner characterization was carried out by recording 73 temperature profiles using a Y-construction thermocouple. Variables considered during these measurements were combustible mixture equivalence ratio, combustible mixture mass flow rates and carrier gas flow rate. A computer program was developed to translate the temperature profiles into isotherms and graphically display these isotherms.

For the ignition studies two different size groups of particles were used. Air and nitrogen were selected and used as carrier gas for the particles in association with three different diameter particle jets.

2.3. Apparatus and Instrumentation

The flat flame burner with the opposed gas-particle jet has been designed, built and modified to meet the following specifications: (a) establish a flat flame under steady-state conditions, (b) provide a gas or combined gas-particle jet along the same axis and in opposed flow to the combustible mixture, and (c) afford temperature and gas composition measurements radially and axially. The six major components of the apparatus are: (i) mixing chamber, (ii) burner tube and porous burner disc, (iii) glass chimney, (iv) stainless steel injection nozzle, (v) flow control and metering system, and (vi) particle feed system. A schematic diagram of the flat flame burner with the opposed gas-particle jet is given in Figure 2.1. The flat flame burner with the opposed gas-particle jet has been used to conduct investigations with metal particles [29-32].

The flow control and metering instrumentation associated with the flat flame burner is shown in Figure 2.2. This schematic shows the original capability of the system. Some modifications and alternatives

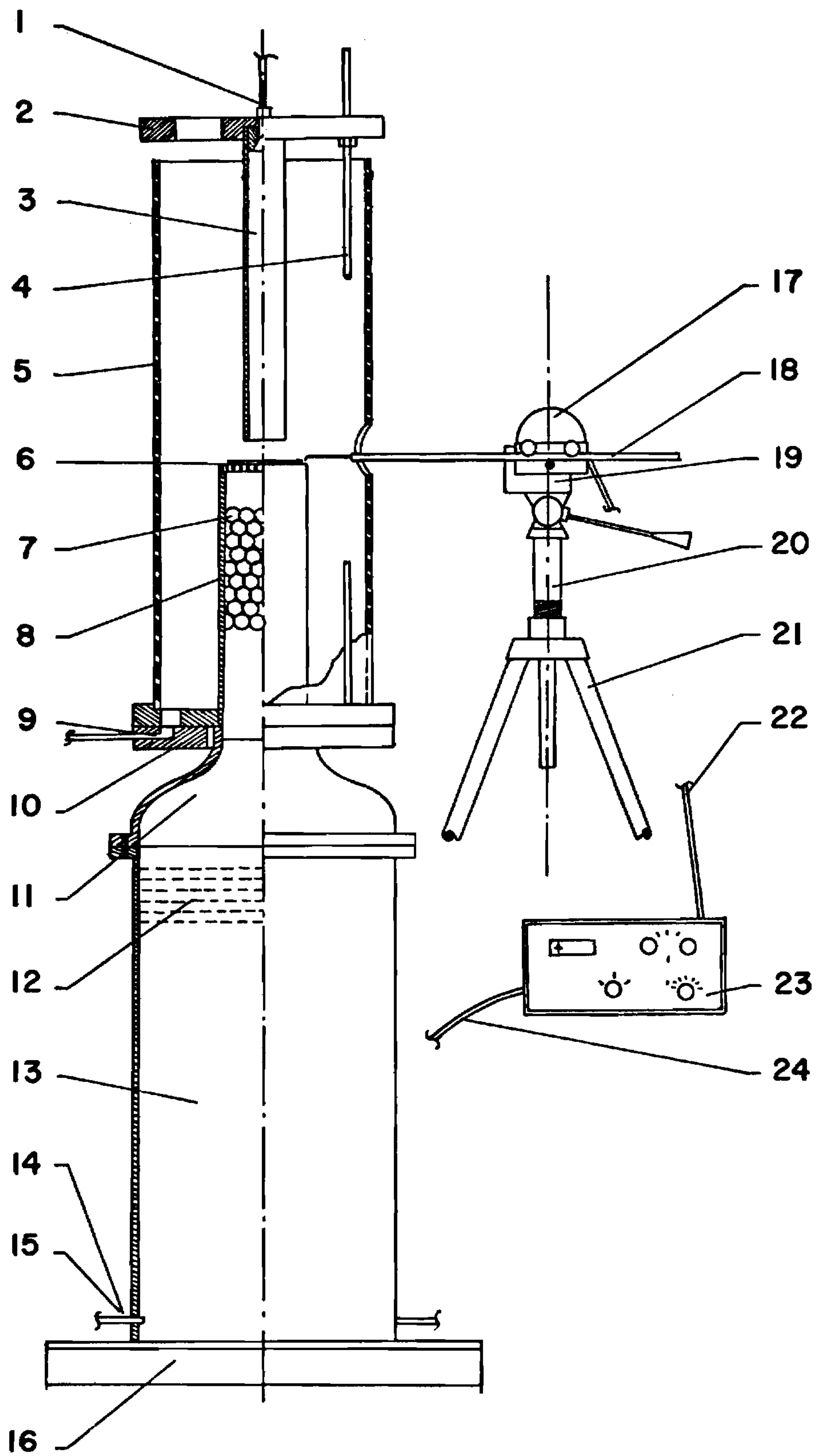

Figure 2.1. Flat Flame Burner Cross-Section and Temperature Probe Traversing Mechanism.

Key to Figure 2.1

1. Particle and carrier gas inlet
2. Injection nozzle supporting ring
3. Stainless steel injection nozzle
4. Supporting rods
5. Pyrex glass chimney
6. Sintered porous bronze burner disc
7. Brass burner tube
8. 3 mm diameter glass beads
9. Gas inlets
10. Aluminum supporting table
11. Cast aluminum transition piece
12. 200 mesh stainless steel screens
13. Mixing chamber
14. Methane inlets
15. Air inlets
16. Steel carriage
17. Stepper motor
18. Thermocouple probe
19. Probe holder for traversing
20. Height regulating sleeve and nut
21. Tripod
22. Stepper motor power input
23. DISA sweep unit generator
24. Sweep unit input

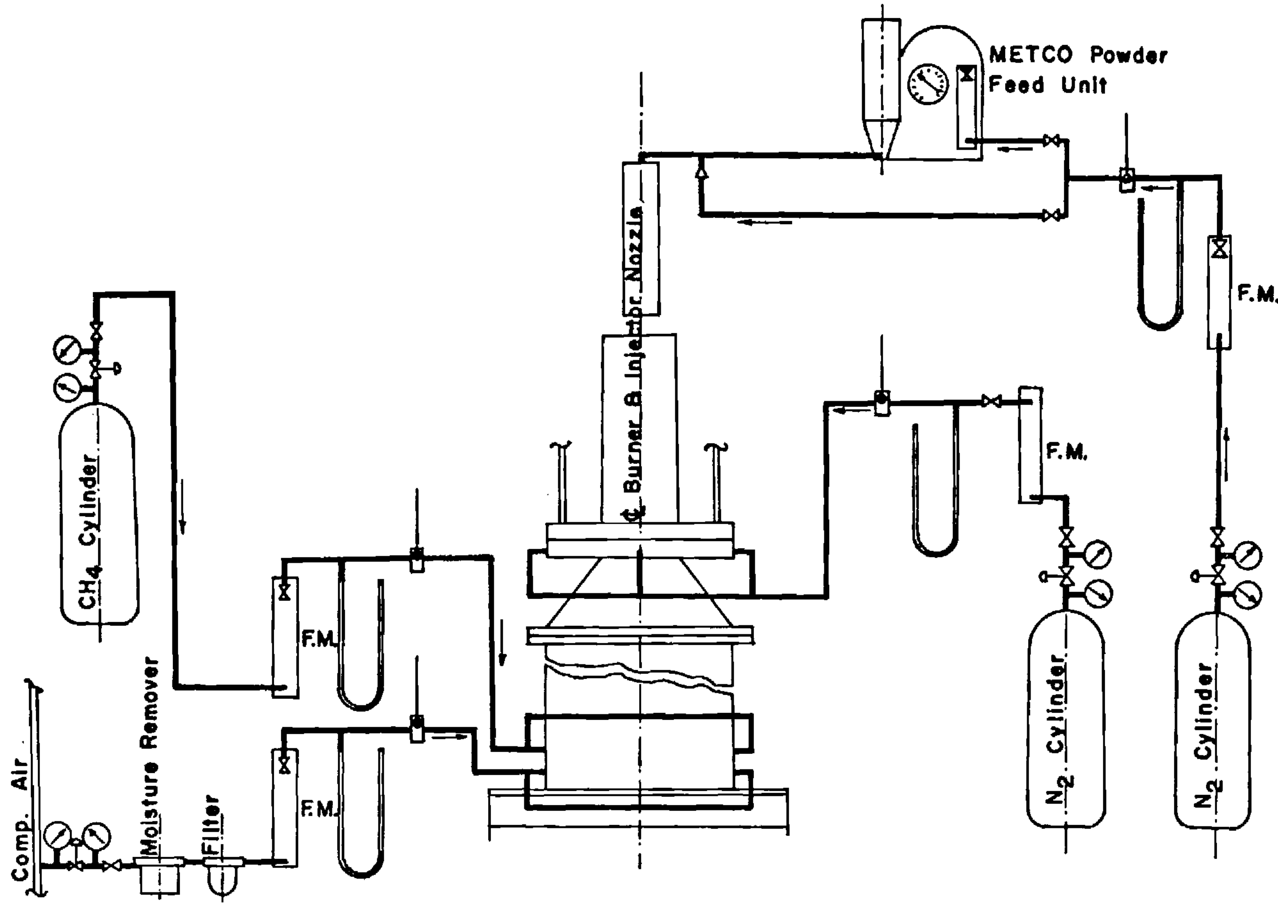

Figure 2.2. Flat Flame Burner Instrumentation and Flow Diagram

have been introduced to increase the flexibility of the system and to adapt it to the needs of the present study. The injection nozzle supporting ring (see Figure 2.1) has been modified to allow use of injection nozzles between sizes of 0.64 and 2.54 cm. The carrier gas supply line has been modified to allow use of a carrier gas ranging from pure nitrogen to pure air.

The Metco Powder Feed Unit shown in Figure 2.2 has been modified and adapted with a screw type particle feed system. This particle feed system has been found suitable for large particles and for high rate of flow of particles. A fluidized bed system coupled with an aspirator has been also designed and built for small particles and low flow rates of these particles. The particle feed system is arranged to use only one of the two particle feed units during any given test.

Associated with the flat flame burner instrumentation is a DISA traversing system (see Figure 2.1) presently used to traverse radially across the burner a Y-construction thermocouple. This system then provides the capability to record on an X-Y plotter the radial temperature profiles at some fixed distance above the burner matrix. A height regulating sleeve and nut on the support of the stepper motor allows the changing of the vertical position of the sweep drive unit. In addition the particle and carrier gas inlet has been modified allowing to insert a thermocouple to measure the centerline temperature.

In the present operation of the flat flame burner the aluminum supporting table for the pyrex glass chimney is provided with ports to allow natural flow of air between the chimney and brass burner tube. It has been observed, however, that this air flows unevenly and with swirling action. Consequently, a screen has been inserted between the brass burner tube and the pyrex chimney. About three layers of 3 mm glass beads were also placed on the top of the screen. This has been found to provide the needed uniformity of flow of the air in the annulus section and around the injection nozzle.

2.4. Experimental Procedure

Most measurements concerning this task require the flat flame burner. Consequently, it is necessary first to put on the fuel and air for the burner, ignite the combustible mixture above the burner matrix and adjust the necessary flow rates to establish a steady-state flame at the desired equivalence ratio and combustible mixture flow rate. Once the desired flat flame has been established the complementary systems such as carrier gas and particle feed systems are activated, adjusted to perform at the desired level and conduct the necessary measurements.

2.5. Results

2.5.1. Fuel and Particle Feed System Characterization

Two coals were selected for these studies. A sample of bituminous coal was obtained from Georgia Power Company. A sample of lignite (brown coal) was obtained from the U.S. Bureau of Mines, Liaison Office, North Dakota. Both fuels were prepared and using screens they were size graded into the groups shown in Table 2.1.

Using two groups of particles, the particle feed systems were characterized in terms of the workable ranges for the system operation.

Table 2.1. Size Grading of Coal Particles

Sieve No.	Screen Opening µm	Coal Size Range µm
40	420	297-420
50	297	210-297
70	210	149-210
100	149	105-149
140	105	74-105
200	74	53-74
270	53	< 53

The screw-type particle system was found unacceptable for use with the smallest group of particles and for providing a low rate of particle flow. The usable range of operation for the two particle feed systems are shown in Table 2.2.

2.5.2. Burner Characterization

Preliminary characterization of the flat flame burner was directed in establishing the usable range of the system. Air and methane had been selected as the components of the combustible mixture and nitrogen or air as the carrier gas. The ranges established are: equivalence ratio ϕ = 0.67 - 0.86; combustible mixture rates $\dot{m}_{cm}$ = 1400 - 2500 g/hr; and carrier gas rates $\dot{m}_{cg}$ = 0 - 180 g/hr.

Table 2.2. Characterization of Particle Feed Systems

Particle Feed System	Particle Size μm	Carrier Gas Rate g/hr	Particle Rate g/hr
Screw Type	297-420	70-180	100-300
Fluidized Bed/ Aspirator	< 53	10-100	2-10

Burner characterization was followed by measurement of temperature profiles in the region 0.3 cm to 1.2 cm above the burner, with and without the carrier gas. Subsequent to these measurements, the developed computer program was utilized to transfer the temperature profiles into isotherms. Two representative isotherm plots are presented in Figures 2.3 and 2.4.

A thermocouple, inserted through the modified carrier gas inlet fitting, has been used to measure centerline temperatures in the injection tube. Representative measurements are shown in Figure 2.5. In this figure the measurements at the edge of the nozzle were made by the traversing thermocouple.

2.5.3. Ignition of Pyrolyzates and Coal

Preliminary tests with coal were carried out using lignite particles 297-420 μm size and the 2.54 cm injection nozzle. The combination of large particle size and high flow rates was found to be undesirable. As soon as particles started flowing out of the injection nozzle they accumulated on the top of the burner matrix, destroying the

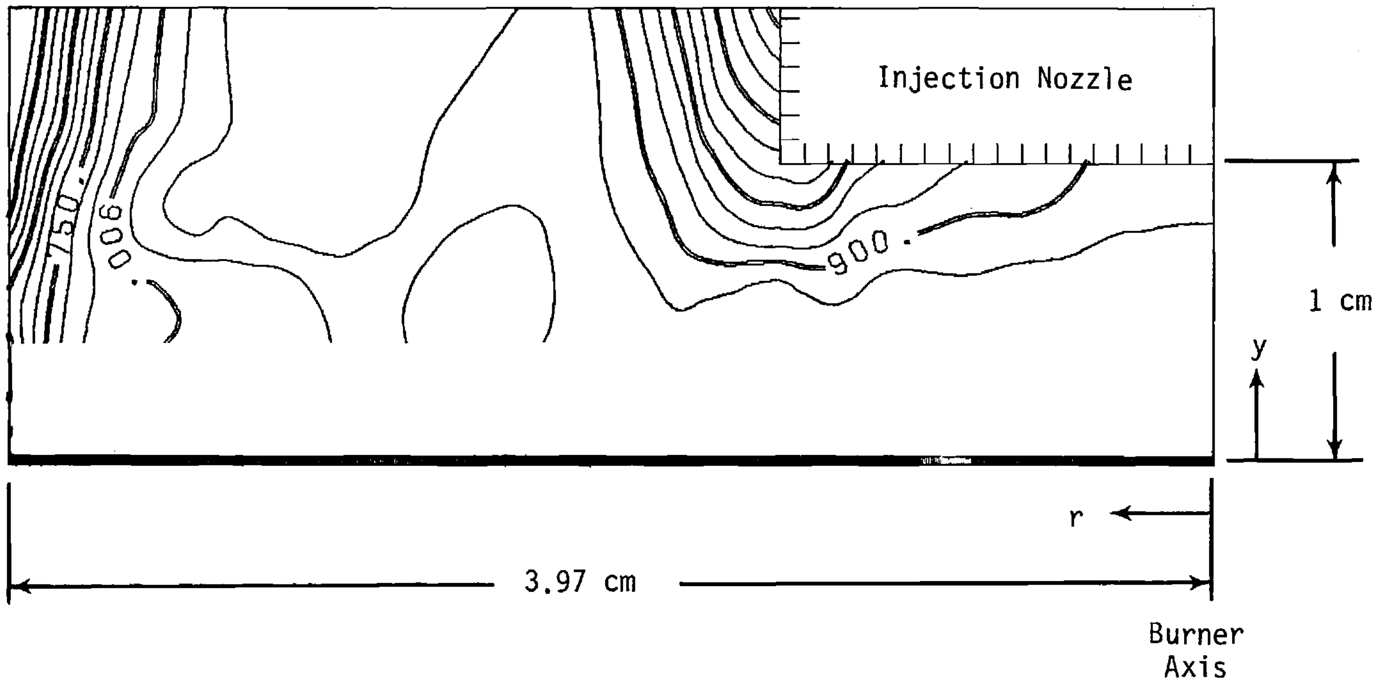

Figure 2.3. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperature in °C, $\phi = 0.67$, $\dot{m}_{cm} = 2440$ g/hr, $\dot{m}_{cg} = 0$, 2.54 cm Injection Nozzle.

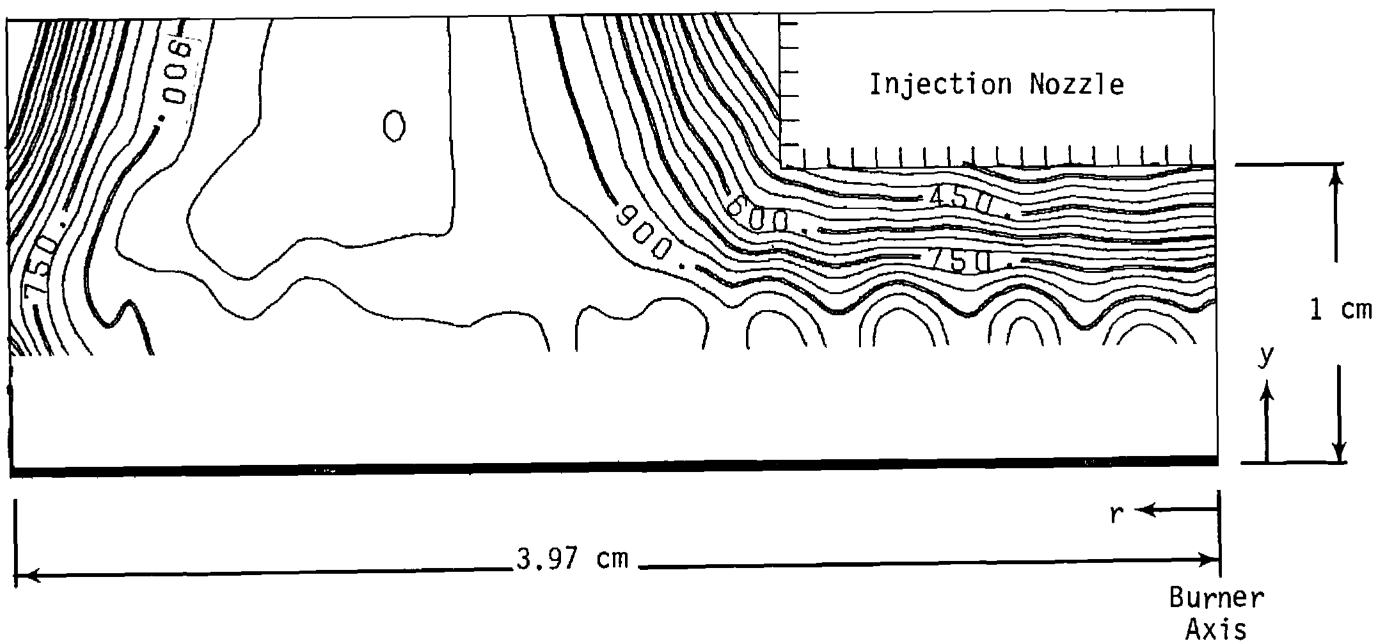

Figure 2.4. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperature in °C, $\phi = 0.67$, $\dot{m}_{cm} = 2440$ g/hr, $\dot{m}_{cg} = 261$ g/hr, 2.54 cm Injection Nozzle.

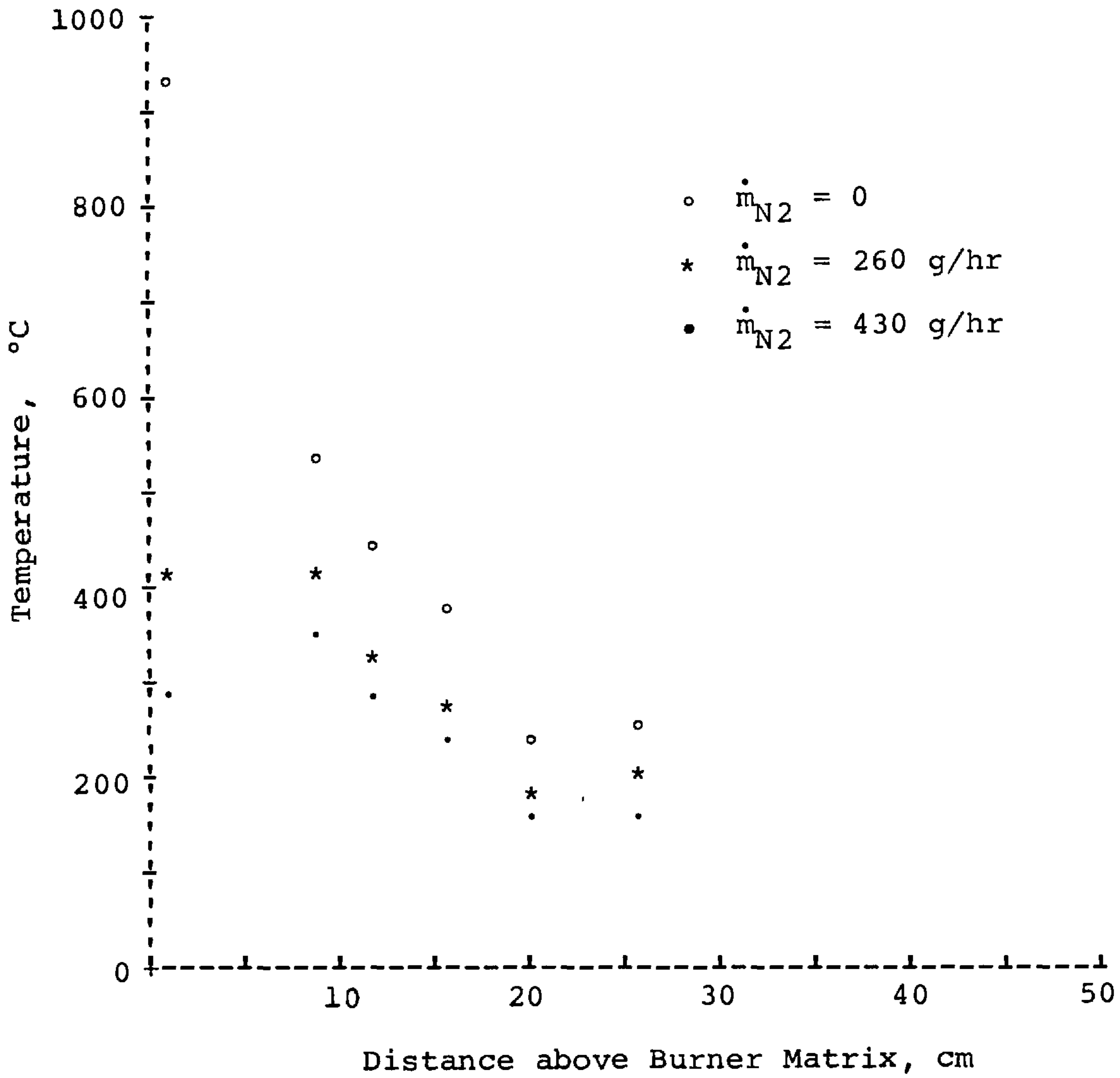

Figure 2.5. Injector Nozzle Centerline Temperatures as a Function of Distance above Flat Flame Burner Matrix, ϕ = 0.67, 2.54 cm Injection Nozzle.

existence of the flat flame.

The next step in the testing program was to use particles of < 53 size. However, with the screw type particle feeder the particle flow could not be controlled and essentially it presented an on and off type of a situation. When the particle flow was on, it also represented a very high flow rate and was unsuitable for any studies.

The design of the combined fluidized bed and aspirator particle feed system was carried out at this point. At the same time, the injection nozzle supporting ring was modified to use smaller diameter injection nozzle tubes. First, the 0.64 cm diameter tube was used. However, for the range of carrier gas flows needed for particle flow, it was found that the exit velocity from the nozzle produced a hole in the flat flame. In other words, the velocity of the opposed flow was high enough to produce an extinction region in the center portion of the flame.

The combinations of < 53 μm size particles, fluidized-bed-aspirator particle feed system, and 0.95 cm diameter injection nozzle tube was found to be desirable. Qualitatively, this produced the first capability of low particle flow rates. Control of the particle flow rates is vested in the adjustment of the carrier gas portion flowing through the fluidized bed and the carrier gas flowing through the aspirator.

Qualitatively, ignition of the pyrolyzate gases was found to depend on the particle flow rate, carrier gas velocity and carrier gas composition. Pyrolyzate ignition was observed to shift from external the injection nozzle tube to the interior of the tube when the carrier gas was changed from nitrogen to air. Also, the flame front produced by the burning volatile gas was found to exist either around the individual particles or merged in a unified front below some distance from the nozzle exit.

2.6. Conclusions

The flat flame burner has been modified for the study of behavior of coal particles in opposed flow to the methane-air combustible mixture. Coupled to the system a screw type particle feed system was found primarily suitable for large particles and large flow rates. A newly designed fluidized-bed-aspirator particle feed system was found capable of establishing low particle flow rates and suitable for small particles.

Ignition of the pyrolyzate gases was found to depend on the particle flow rate, carrier gas velocity and carrier gas composition.

3. RAPID PYROLYSIS OF COAL

3.1. Purpose

The purpose of the coal pyrolysis investigation is to study the effect of initial atmosphere and heating rate during pyrolysis on the composition and ignition characteristics of pyrolysis gases. The rapid pyrolysis apparatus known as the Lower Ignition Temperature and Concentration Apparatus (LITACA), which has been used in pyrolysis studies of cellulosic and thermoplastic materials [21], will be modified for use with coal. The pyrolysis study will focus on the degree of pyrolysis as a function of type of fuel, initial atmosphere and rate of heating during pyrolysis. The pyrolysis gas characteristics will be classified in terms of minimum ignition temperature of these gases as a function of pyrolyzate-air concentration, flammability limits and apparent molecular weight of pyrolysis gases.

3.2. Achievements

Minor modifications were carried out on the Lower Ignition Temperature and Concentration Apparatus (LITACA). To test the reaction cell and establish procedures for ignition tests through the reaction cell with gaseous fuels, a total of 55 ignition runs were carried out with methane (CH_4), propane (C_3H_8) and butane (C_4H_{10}).

Using bituminous coal particles that have been sized into the groups of < 62 μm and 149-247 μm the total of fifteen pyrolysis runs were carried out at two heating rates and with four different initial atmospheres in the sample tube of the furnace. From each pyrolysis run at least one gas sample was drawn to determine the apparent molecular weight of the generated gaseous fuel. The remainder of the pyrolyzate gases were used to conduct the total of 74 ignition temperature measurements at various air-fuel concentrations. Samples of the coal particles and of the residual chars after pyrolysis were also used to take the total of five electronmicrographs of these samples.

3.3. Apparatus and Instrumentation

The Lower Ignition Temperature and Concentration Apparatus (LITACA) has been designed, built and modified to meet the following specifications: (a) thermally decompose pyrolyzing materials, (b) store the pyrolyzates, (c) mix the pyrolyzates with dry air at controlled mass fractions, (d) measure the minimum mixture temperature at which self-ignition occurs, and (e) afford pyrolyzate sampling for molecular weight determinations. The six major components of LITACA are: (i) pyrolyzate generating furnace, (ii) volatile reservoir, (iii) pyrolyzate and air metering system, (iv) reaction cell, (v) temperature recording and ignition detection instrumentation, and (vi) pyrolysis timing and power control equipment. A schematic diagram of LITACA is given in Figure 3.1.

LITACA has been used to pyrolyze fabrics and wood [21]. The ignition characteristics of the pyrolyzate gases generated from these materials were determined at heating rates from 20 to 6000°C/min. The apparatus has been used for the current studies on coal pyrolysis with only minor modifications. These consisted of some changes in the

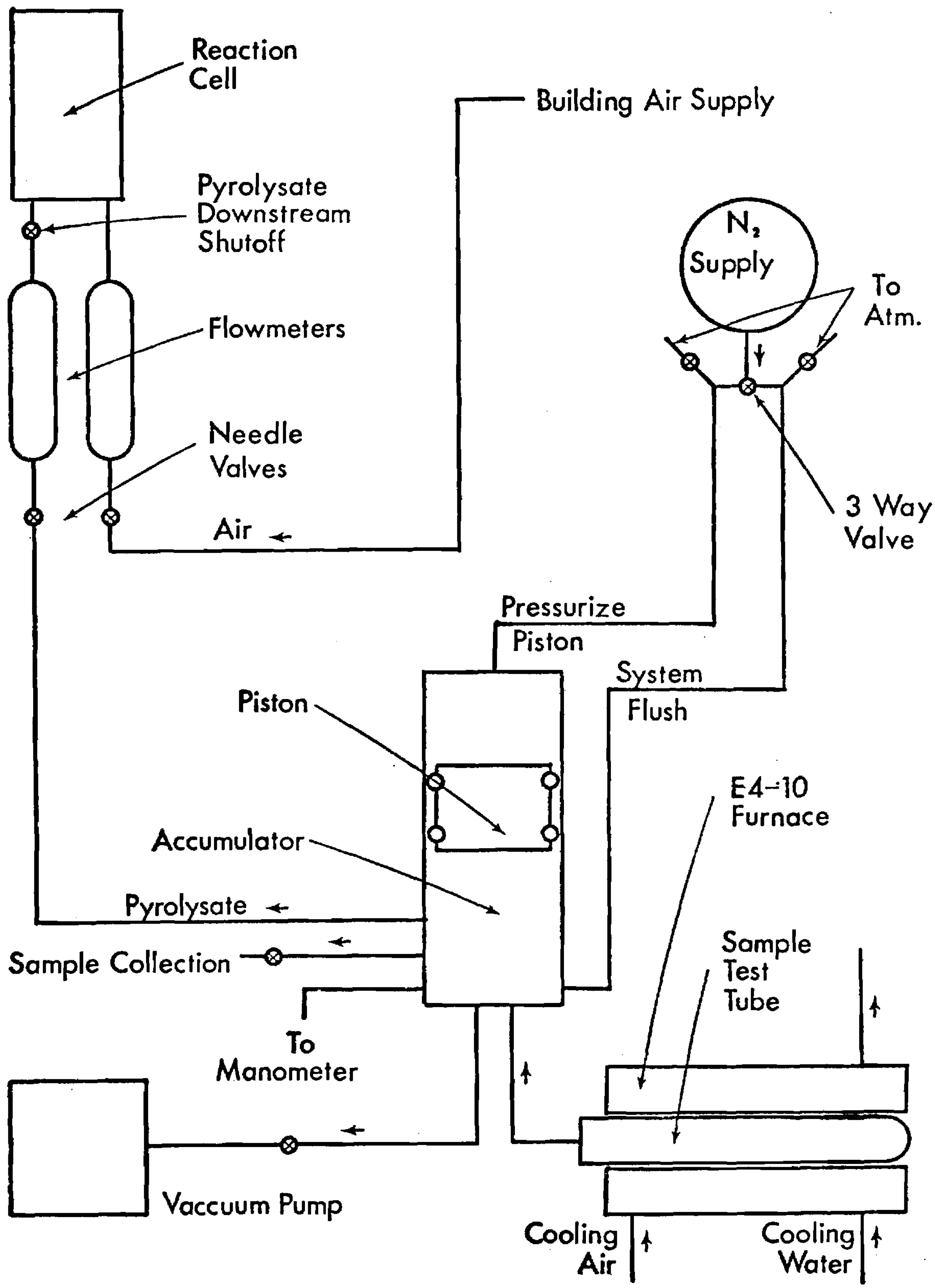

Figure 3.1. Lower Ignition Temperature and Concentration Apparatus (LITACA) Schematic.

tubing, guard heating and gas metering system. In addition, a stainless steel screen support has been manufactured which goes into the quartz sample holder tube and is used to support the coal particles spread out in the center of the tube. The quartz sample holder tube used with the furnace is 2.5 cm I.D. and 38.6 cm long. This tube has a flange connection on one end and closed at the other end. A second quartz sample holder tube has also been manufactured which is 2.5 cm I.D. and has a flange connection on both ends of the tube and is 43.2 cm long. Finally, the balloons used to collect a sample of the pyrolyzate gas for apparent molecular weight determination were modified and outfitted with a vacuum petcock.

3.4. Experimental Procedure

3.4.1. Pyrolysis

The minimum self-ignition temperature measurements on pyrolyzate-air mixtures require that the material being tested must first be pyrolyzed and then the gaseous products must be stored until they are ready to be used for the self-ignition temperature tests. For each pyrolysis run approximately a 25 gram of coal sample was used. It was then loosely placed on the stainless steel screen and inserted into the sample holder tube. The sample tube was then placed in the furnace and properly attached to the system.

Before initiating the pyrolysis of the sample materials, all guard heaters were turned on and adjusted to maintain a temperature of about 120-140°C. Then the system vacuum pump was turned on and a vacuum of approximately 10^{-1} μm Hg was drawn on the system. The vacuum pump was then turned off to check the system for leaks. If after a period no loss in vacuum was observed the system was flushed with nitrogen or air and evacuated twice before a final pressure was established for the pyrolysis runs with the appropriate gas.

The pyrolysis runs conducted with the radiant heater furnace included a preheat period. The preheat auto-transformer of the radiant heating furnace was, therefore, set to provide a temperature of 140-150°C in the furnace when the heating cycle would be initiated. This same transformer controlled also the postheat temperature in the furnace. The furnace auto-transformer was adjusted to provide the desired voltage and heating rate during pyrolysis. For the tests reported here, it was selected to carry all pyrolysis runs to completion. The preheat period was of about two minute duration for all pyrolysis runs and it normally took between 17 minutes and 25 minutes to complete the pyrolysis process depending on the selected pyrolysis heating rate.

During the pyrolysis runs the top of the accumulator piston was vented to the atmosphere and consequently the volume expanded once the pressure in the system exceeded one atmosphere. When the pyrolysis process was completed, the piston vent valve was closed and the top of the accumulator piston was pressurized with nitrogen to provide a pressure in the accumulator of about 50 cm Hg gauge.

3.4.2. Self-Ignition Temperature Measurements

The minimum self-ignition temperature measurements were initiated by turning on the air and the air flowmeter adjusted to provide the desired level of flow. Next, the preignition heater and the ignition heater auto-transformers were turned on. Finally, the gas fuel valve was turned on and the flowmeter valve adjusted to provide the desired level of flow.

Three thermocouples in the ignition tube were used to continuously record the temperature of the gases on the strip chart recorders. By monitoring the temperature history of the fuel-air mixture flowing through the ignition tube, the minimum self-ignition temperature can be determined. Two different categories of ignition signals were used and these are shown in Figures 3.2 and 3.3. The quenching reaction (Q.R.) signal occurred primarily near the lean limit. As soon as ignition was detected, all pertinent data was recorded, the pyrolyzate flow was turned off, all reaction cell heaters were turned off, and the air flow was turned on full to purge the ignition tube and cool the reaction cell.

If ignition did not occur by the time the maximum temperature thermocouple reached 1000°C, the test was terminated. The reaction cell heaters and the fuel supply were turned off.

3.4.3. Molecular Weight Measurements

Before initiating the pyrolysis in the furnace sample tube preparations were carried out for the molecular weight measurements. These consisted of turning on the oven, evacuating the balloons and after weighing them, placing them in the oven. Once the pyrolysis process was completed, one of the balloons was used to draw the pyrolyzate gases in the evacuated balloon and the balloon returned to the oven. When the balloon established a thermal equilibrium with the oven, the balloon petcock was opened to depressurize it and allow it to reach pressure equilibrium with the atmosphere. The balloon full of pyrolyzate gas was then weighed and using the tare weight of the balloon the net weight

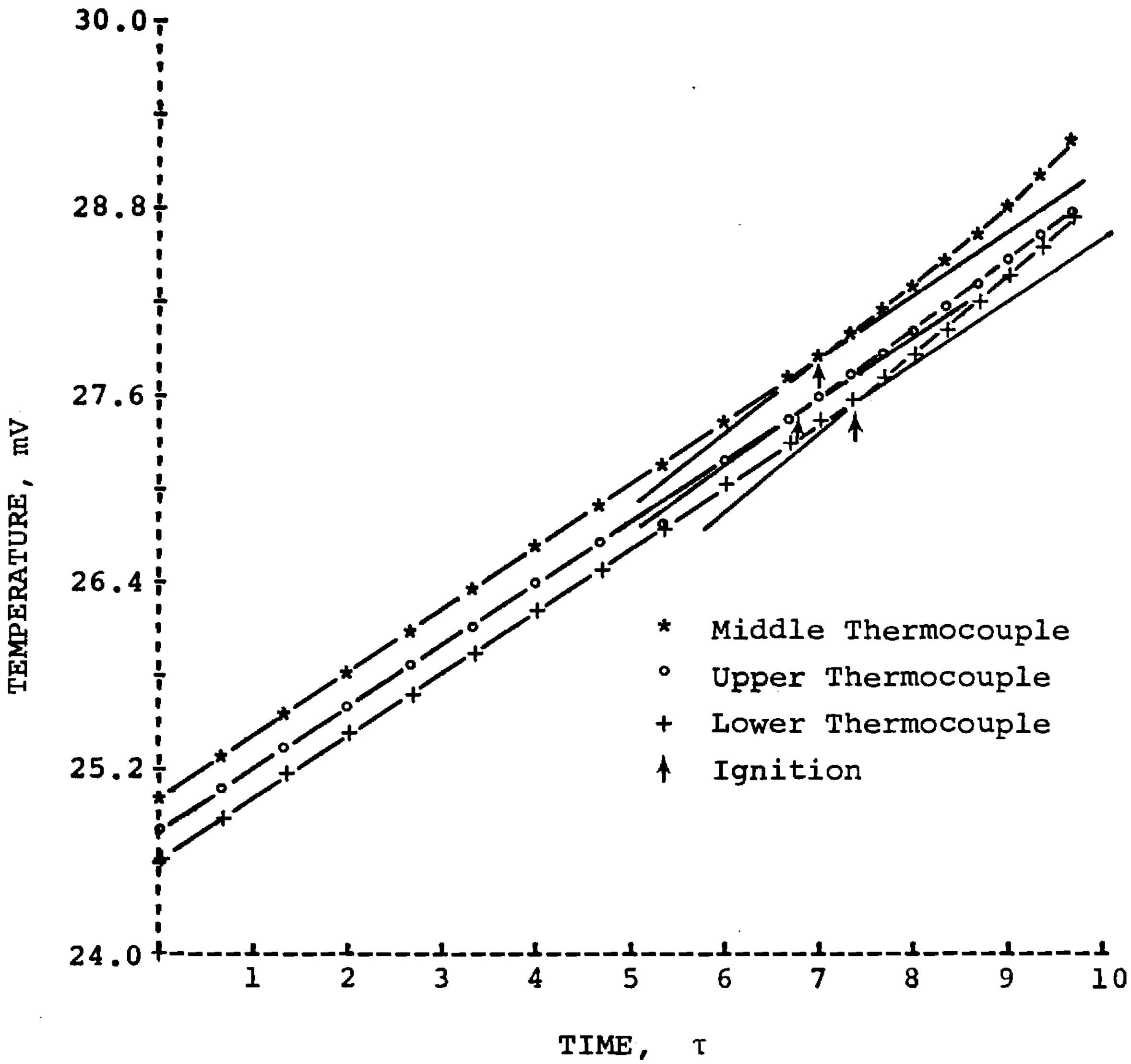

Figure 3.2. Detection of Pyrolyzate Ignition.

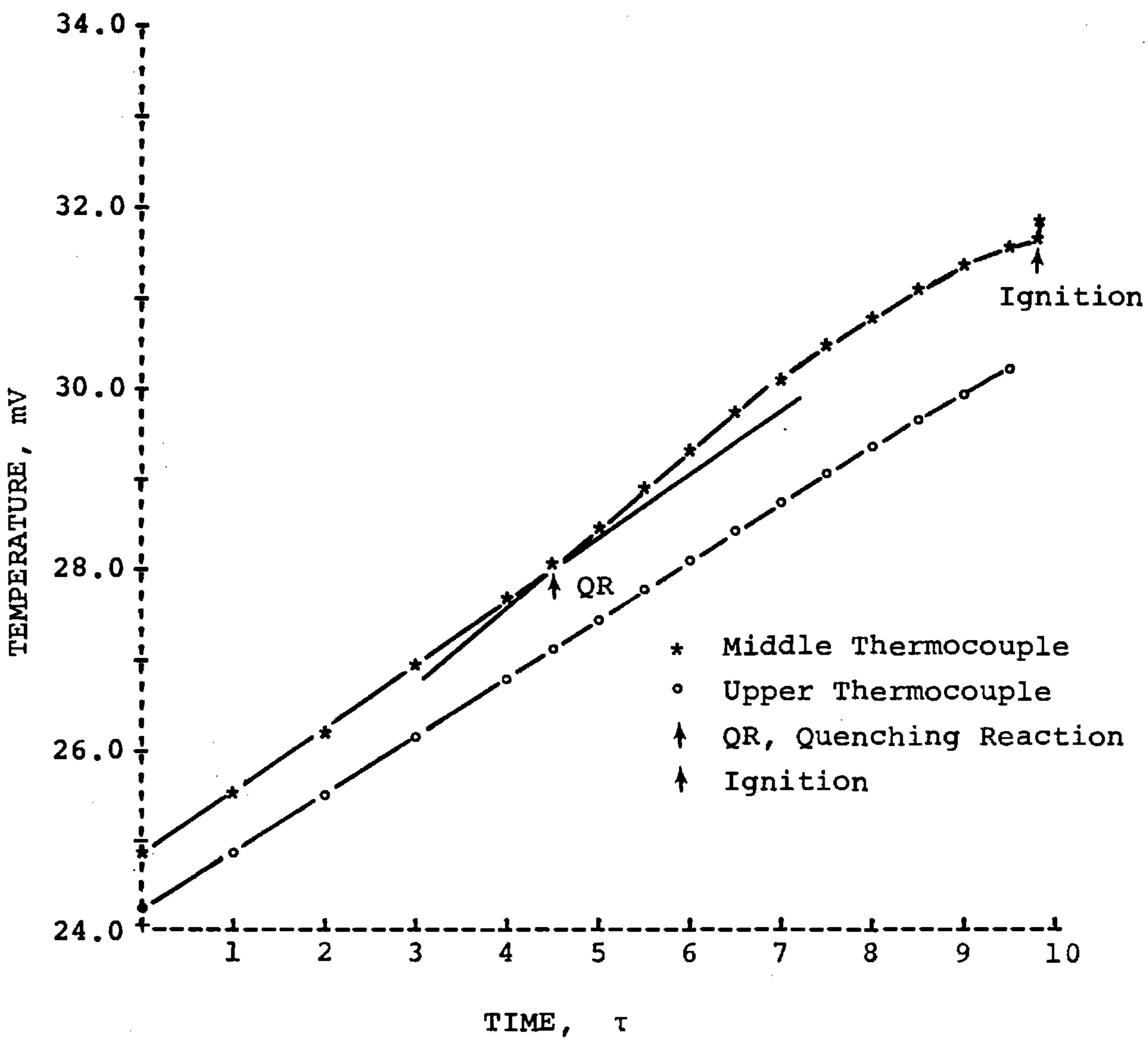

Figure 3.3. Detection of a Quenching Reaction Followed by Ignition.

of the pyrolyzate gas was established.

3.5. Results

Bituminous coal was ground and sized and for the tests reported here two groups of particles were selected for the pyrolysis tests. The first group contained coal particles less than 62 μm and the second group consisted of coal particles in the range 149-247 μm. The pyrolysis of coal was carried out with initial heating rates of 1000°C/min and 2600°C/min representing available power to the tungsten filament infrared lamps of the furnace of 5 W/cm^2 and 10 W/cm^2, respectively, for the 25.4 cm length. These heating rates and heating rates selected to be used during future studies are comparable to those encountered by the particles in the flat flame burner with the opposed gas-particle jet discussed in Section 2 of this report. An initial atmosphere of trace nitrogen, trace air and 18-20 cm Hg nitrogen was also used as a variable.

The results of minimum self-ignition measurements on pyrolyzate gases generated at the two heating rates are presented in Figures 3.4 and 3.5. As illustrated in the figure, a significant difference in the ignition behavior was found between the measurements performed on gases generated at the lowest heat rate of 1000°C/min and those generated at the higher heating rate of 2600°C/min. Primarily the difference is on the fuel-rich side of the curve where the ignition points show a very large scatter with respect to temperature at the 1000°C/min heating rate. At the same time, a narrower flammability range appears to exist for this lower heating rate. However, no apparent difference in the ignition temperatures exist among the gases generated at the three

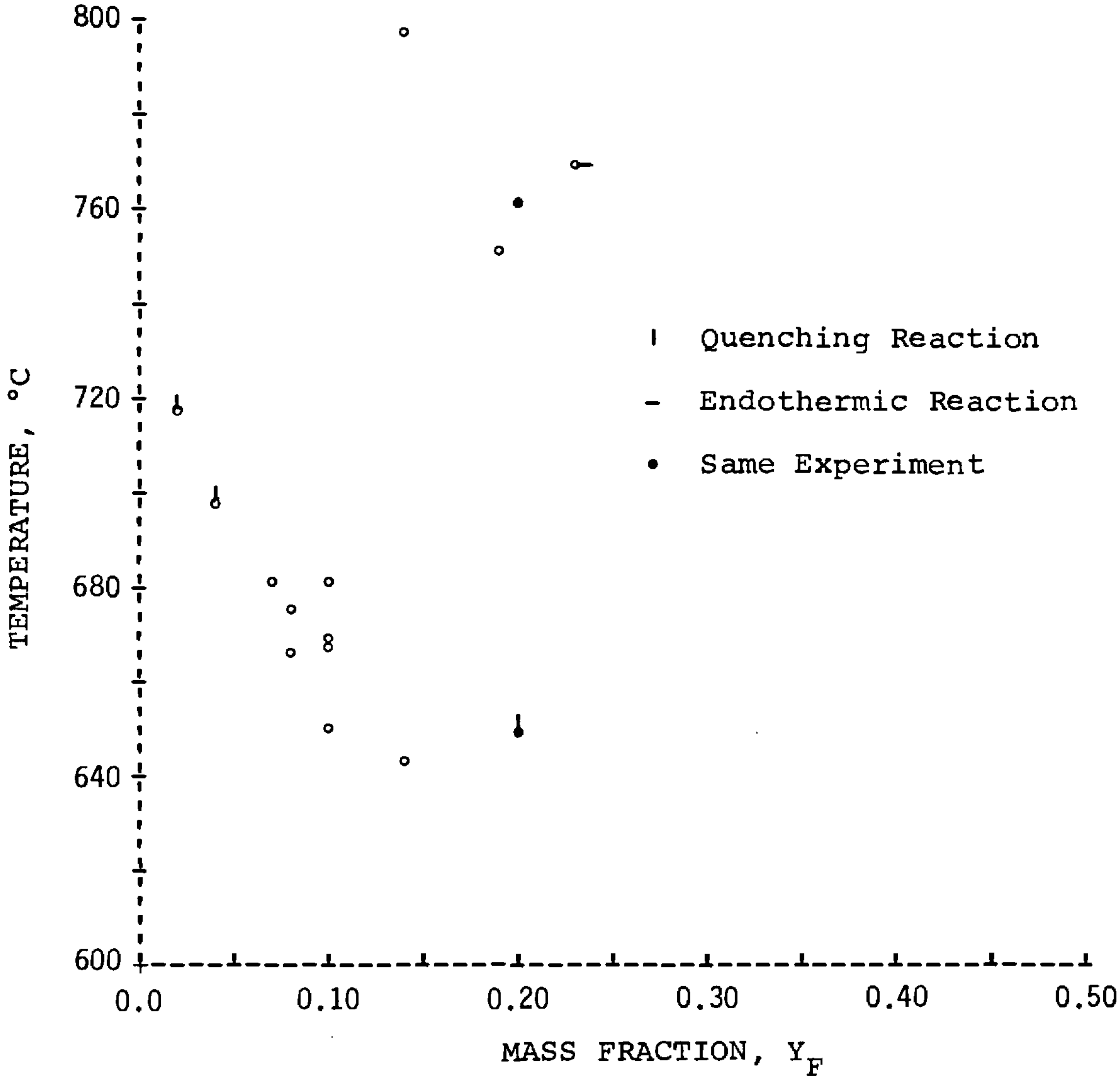

Figure 3.4. Ignition Temperature of Pyrolysis Gases Generated at a Heating Rate of 1000°C/min, Bituminous Coal Particles 149-247 μm, N_2 Trace.

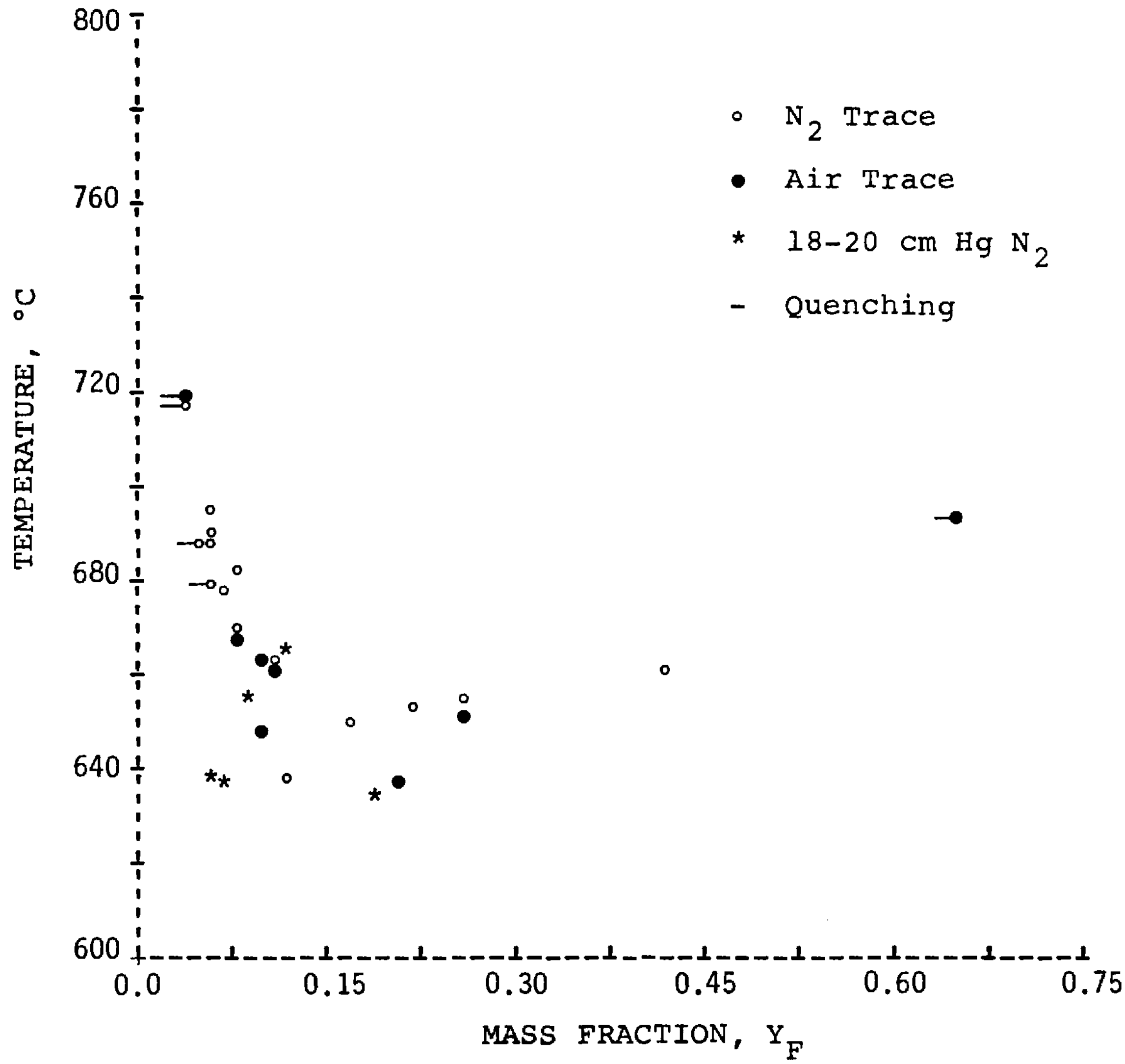

Figure 3.5. Effect of Initial Atmosphere on Ignition Temperature of Pyrolysis Gases Generated at a Heating Rate of 2600°C/min, Bituminous Coal Particles < 62 µm.

different initial atmospheres.

For each pyrolysis run one or more gas samples were taken from the accumulator to conduct an apparent molecular weight measurement. These were averaged for each heating rate and the results are presented in Table 3.1. It is evident from these measurements that with increase in the heating rates for pyrolysis the gas composition shifts to larger fraction of low molecular weight components.

Table 3.1. Apparent Molecular Weights of Pyrolyzate Gases

Heating Rate °C/min	No. of Tests	Molecular Weight g/g-mole	Standard Deviation
1000	7	21.0	1.26
2000	4	17.7	1.11

3.6. Conclusions

The Lower Ignition Temperature and Concentration Apparatus (LITACA) has been modified and used in the rapid pyrolysis of coal. The characteristics of the generated pyrolysis gases were classified in terms of the minimum ignition temperature of these gases.

The effect of the heating rate during pyrolysis, for the fuel and heating rates tested, was found to be a broadening of the flammability limits, and the reduction of the apparent molecular weight of the gases, with increasing heating rate.

No change in the ignition characteristics of pyrolysis gas was found with changes in the particle size and changes in both composition and pressure of the initial atmosphere.

4. COMBUSTION OF COAL AND CHAR

4.1. Purpose

The purpose of the coal and char combustion task is to study the effect of regenerative pyrolysis on the combustion of the particles. The flat flame burner with the opposed gas-particle jet will be used for these studies. Variables to be considered are the type of fuel, particle size, level of preheating, composition of the carrier gas, and composition of the oxidizing atmosphere.

4.2. Achievements

This task is not scheduled to start until some later time in the program. The modifications carried out on the flat flame burner, gas-particle jet and particle feed systems are also pertinent in these studies. Beyond these changes discussed in Section 2, very few minor changes will be needed for use of the apparatus for this task.

5. PRELIMINARY MODELING ANALYSIS

5.1. Introduction

It is of interest to couple the experimental program of the regenerative pyrolysis of coal particles with mathematical modeling of the various processes encountered. However, preliminary studies shall concentrate on the mathematical description of the processes within the carrier-gas-particle injector nozzle.

The objective of the present analysis, then, is to predict: (i) velocity, temperature and concentration profiles throughout the particle injector nozzle and (ii) heating conditions that will lead to pyrolysis and ignition of the coal particles within the nozzle.

5.2. Problem Formulation

The model assumes steady state conditions of a solid-gas mixture flowing through a heated, constant area duct (see Figure 5.1). The particle injector nozzle wall is assumed to have a known temperature distribution that varies along its length. This temperature profile may be specified from experimental measurements discussed in earlier sections of this report. Throughout the nozzle the coal particles and carrier gas are assumed in local thermodynamic equilibrium. At the nozzle entrance the particle density, carrier gas composition and solid-gas mixture flow rate and temperature are assumed known. Pressure effects are neglected and thermophysical properties and reaction

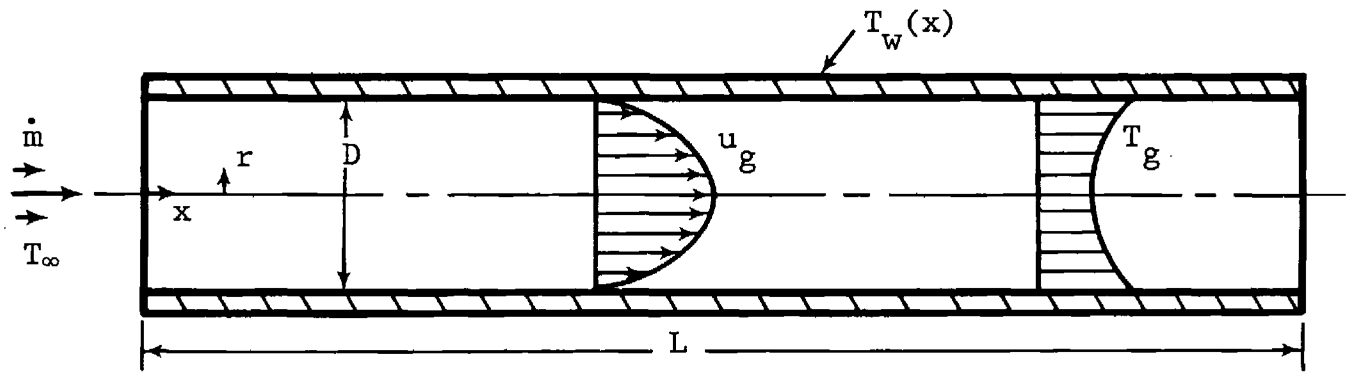

Figure 5.1. Coordinate System of the Gas-Particle Flow System Heated through the Wall.

kinetics parameters are assumed to be constant.

5.3. Model Simplifications and Parameter Ranges

The variables affecting the pyrolysis and ignition of the coal particles are: (i) heating rate of the solid-gas mixture, (ii) the mixture flow rate, (iii) the nozzle dimensions, (iv) the particle density, and (v) the initial carrier gas composition. The intimate interactions of these variables makes evident the complexity of the analysis.

To develop a preliminary understanding of these variables and their influence on regenerative pyrolysis and coal particle ignition, further simplifications are made. In addition, the experimental flow rates, temperatures and nozzle dimensions of Task I are used to determine rough estimates of the variable ranges.

Calculations are based on the carrier gas flow rates and neglecting particle effects. For the range of carrier gas mass flow rates and the range of nozzle diameters selected, the Reynolds numbers are well within the laminar flow regime for duct flow. Assuming steady, incompressible laminar flow within a constant area duct and with constant properties, the centerline velocity may be calculated [33]. From the nozzle length and centerline velocity, the centerline residence time for a fluid element may be determined. If this fluid element enters the nozzle at the ambient temperature and exits the nozzle heated to some elevated temperature (300 K and 800 K, respectively), a heating rate is obtained using the residence time. Table 5.1 lists estimated values for these parameters. Note that the carrier gas is

Table 5.1. Estimated Values of Parameters for the Heated Gas-Particle Flow in a Duct

Nozzle Diameter d cm	Carrier Gas Flow Rate $\dot{m}_{cg}$ g/hr	Reynolds Number Re_d	Centerline Velocity u_o cm/s	Centerline Residence Time τ_o s	Heating Rate °C/min	Feeder Type
0.635	10	9.23	21.3	1.34	2.239×10^4	Aspirator
	100	92.3	213.0	0.13	2.239×10^5	
	70	137.6	149.1	0.19	1.579×10^5	Screw
	180	353.6	383.3	0.074	4.054×10^5	
2.54	10	36.9	1.33	21.4	1.402×10^3	Aspirator
	100	369.0	13.3	2.14	1.402×10^4	
	70	34.4	9.32	3.06	9.804×10^3	Screw
	180	88.6	24.0	1.19	2.521×10^4	

assumed to be air and that its density and dynamic viscosity have been evaluated at one atmosphere and an effective nozzle temperature of 600 K.

6. PUBLICATION AND PRESENTATIONS

The research results, of the present grant period on the combustion of coal in an opposed gas-particle jet with regenerative pyrolysis, have been presented as follows:

(i) Durbetaki, P., "Combustion of Coal in an Opposed Gas-Particle Jet with Regenerative Pyrolysis," Combustion Phenomena Contractors Review Meeting, United States Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, 19 September 1979.

(ii) Wolfe, V. L., Jr., McAuliffe, G. H., and Durbetaki, P., "Preliminary Studies in Rapid Pyrolysis of Coal," 1979 Technical Meeting, The Eastern Section, The Combustion Institute, Georgia Institute of Technology, Atlanta, GA, 7-9 November 1979.

An extended abstract of presentation (ii) above was published in the book of abstracts.

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E-25-611

FINAL REPORT

COMBUSTION OF COAL IN AN OPPOSED GAS–PARTICLE JET WITH REGENERATIVE PYROLYSIS

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Prepared for

Office of University Activities
U.S. Department of Energy
DOE Grant No. FG22–78ET–13411

31 August 1980

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Final Report

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Prepared for
Office of University Activities
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DOE Grant No. FG22-78ET-13411
(Formerly E7-78-G-01-3305)

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ACKNOWLEDGEMENTS

The work presented in this report was carried out with the support of the Department of Energy (DOE) Grant No. FG22-78ET-13411 (formerly Grant No. ET-78-G-01-3305). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE.

ABSTRACT

The burning of coal particles is the coupled effect of the interlinked processes of pyrolysis, ignition and combustion of the volatiles and char. The preliminary study presented in this report is an effort in that direction. The specific objectives for the current research program are: (i) to establish an operating system with regenerative pyrolysis, (ii) to identify the primary parameters which effect the pyrolysis, ignition and combustion of the particles in this system, (iii) to identify measurements which are needed and techniques to be developed for these measurements, and (iv) to establish a preliminary basis for a modeling analysis. The present studies carried out with the flat flame burner and the opposed gas-particle jet have shown the feasibility of studying the ignition of pyrolyzate and coal particles. These were found to be affected by the level of preheating, composition of carrier gas and type of fuel particle. The behavior of lignite particles compared to bituminous particles were found to be distinctly different. Pyrolysis experiments carried out on the two coals at heating rates near those experienced with regenerative pyrolysis, have shown that self-ignition temperatures of fuel lean mixtures are not effected by the variable considered in this investigation. Fuel rich mixture self-ignition temperatures were found to depend on the magnitude of the initial atmosphere. In these experiments differences between bituminous and brown coal have also been observed. Sooting was found to accompany the combustion of bituminous coal particles and not of the lignite particles. Also higher gas-particle rates were found to be needed to self-sustain the combustion of bituminous coal particles than those required for lignite coal particles. These preliminary studies in the three areas of ignition, pyrolysis and combustion have shown the need to use additional instrumentation to further quantify the behavior of these coal particles under regenerative pyrolysis conditions.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure | Page

Figure | Page

LIST OF TABLES

1. INTRODUCTION

1.1. Background

Current usage and future applications of pulverized coal as an energy resource dictates a broad range of systems and conditions. When pulverized coal particles are injected into a hot oxidizing atmosphere, such as a furnace, at a rate of about 25,000 kg/h, the coal undergoes rapid heating, of the order of $10^4 - 10^5$ degrees C per second, with some volatile loss, ignition and combustion of the volatiles and char [1]. When pulverized coal is used in conjunction with gaseous and liquid fuels for combustion and where these fuels constitute the carrier fluid, the heating rates encountered by the coal particles are somewhat reduced. Further, when coal particles suspended in a gaseous stream are simultaneously being heated, the heating rates are lower by several orders of magnitude [2]. The characteristics of each of these and other processes ranging within these broad limits, as well as the associated processes of volatile loss, ignition and combustion vary quite significantly depending upon the size distribution of the coal particles and the environment of the system. In as much as, residence times vary with each of the processes and efficient combustion of the entire coal particle requires an optimal execution of the pyrolysis, ignition and combustion processes, the conditions and parameters responsible for such an occurrence must be sought, investigated and quantified.

The ignition and combustion behavior of pulverized coal particles have been investigated extensively in the U.S. and abroad [3-14]. However, many aspects of these processes have been determined only qualitatively [9-15]. Reviews on the qualitative and quantitative aspects of this problem can be found in four papers published during the last decade [1,9,15,16].

A century long held notion was that the ignition of coal always occurs in the gas phase. Presently, it is still common to relate the ignition characteristics of coal on the flammability of the volatile gas of coal [17]. Howard and Essenhigh [5,18] were the first to disprove experimentally such an occurrence for all coal particles and later by Thomas et al. [19], Bandyopadhyay and Bhaduri [20], and Annamalai and Durbetaki [13,21]. Thus there is evidence that for partially pyrolysing material like coal, ignition occurs both at the surface and in the gas phase. The mode of ignition depends upon particle size, volatile content, ambient oxygen concentration and pressure.

The existence of volatiles in the fuel and their effect during the combustion process is very important. With cellulosic material it has been observed that the heating rate during pyrolysis has a pronounced effect on the composition and ignition characteristics of the pyrolysis gases [22]. In atmospheric combustion of coal the pyrolysis generally takes about ten percent of the total combustion time. Variables such as pressure, particle size, particle dispersion and rate of heating are important in establishing the amounts of volatile yield during pyrolysis [23-26].

Another interesting result in the burning of carbon at low pressure is that the reaction rate shows a peak at some surface temperature of the carbon/char [27] and this is true even at very low pressures [28]. The results point out that the increasing pressure has the tendency to shift the peak reaction rate towards a higher temperature [12,14]. Such a shift in the temperature is very desirable for some power generating systems.

Howard and Essenhigh [5] have shown that there exists a certain critical particle size for the coal particles where the flame just anchors on the particle surface. This fact leads to the conclusion that for a particle size below this critical value there could be no gas phase combustion [5,17]. Recently Annamalai and Durbetaki [29] have obtained critical sizes for the gas phase extinction of flames for coal particles and hydrocarbon droplets by extending the theory of Spalding for opposed jet diffusion flame. These critical sizes give only a sufficient condition for extinction, once a flame is established.

The above discussion and summary of past work makes it evident that there exist uncertainties with regard to the ignition phase of coal particles, pyrolysis, combustion of char and extinction of burning coal particles. The study reported here is an initial effort in providing some understanding of the processes involved during various stages of the combustion of coal particles and their interaction to provide efficient burning of these particles.

1.2. Relevance

Ignition and combustion behavior of coal particles have been investigated extensively in the U.S. and abroad. However, many aspects of these processes have been determined only qualitatively and some of the information available cannot apply to the broad range of system conditions. The expanding use of coal requires design of equipment to process and introduce the fuel in the combustion systems. In some instances there is also a need to modify and improve the performance of existing equipment. In all these cases, it is pertinent that the design is a result of a fundamental understanding of how the various processes in the burning pyrolysis and gasification of coal particles interact, as well as what are the critical parameters needed to achieve an optimum operation of the system.

The method of regenerative pyrolysis, initiated with the studies reported herewith and to be the basis of future investigations, is expected to provide a fundamental understanding of operating conditions and values of those variables which will bring about an enhancement in the burning, pyrolysis and gasification of coal particles. It is also expected that this research will provide a basis for studies concerning environmental aspects of coal utilization. For example, the regenerative pyrolysis process will enable the system to operate at lower temperatures and consequently reduce the production of oxides of nitrogen. Furthermore, the current and future programs make it possible to continue and expand the training of students at both the undergraduate and the graduate level in the combustion, pyrolysis and gasification of coal. Consequently, these studies are relevant from an economical, environmental and educational point of view.

1.3. Current Program Objectives

The burning of coal particles is the combined effect of the interlinked processes of pyrolysis, ignition and combustion of the volatiles and char. Efficient burning of these particles requires an understanding of the various processes and their respective influence on the entire cycle. The overall objective of this investigation is to study the effect of regenerative pyrolysis on the combustion of coal. The specific objectives for the current research program are: (i) to establish an operating system with regenerative pyrolysis, (ii) to identify the primary parameters which effect the pyrolysis, ignition and combustion of the particles in this system, (iii) to identify measurements which are needed and techniques to be developed for these measurements, and (iv) to establish a preliminary basis for a modeling analysis.

The program reported here consists primarily of experimental studies and one task in modeling analysis. The program was divided into four tasks:

Task 1. Ignition of Pyrolyzates, Coal and Char

Task 2. Pyrolysis of Coal

Task 3. Combustion of Coal and Char

Task 4. Preliminary Modeling Analysis

The regenerative pyrolysis of coal studies (Task 1) and the sustained combustion of coal studies (Task 3) were carried out using a flat flame burner with an opposed gas-particle jet. These studies were coupled with measurements using a Lower Ignition Temperature and Concentration Apparatus (Task 2). These studies provide variable heating rates and initial atmosphere for coal pyrolysis, to generate pyrolysis gases and use these for characterization.

1.4. Summary

Details of the program accomplishments during the research grant period are presented in the chapters which follow. Chapters 2, 3 and

4 are devoted to the experimental program and present equipment modifications, new equipment and instrumentation development, test procedures and test results. Some of the details on the equipment are included in the Appendices. The preliminary modeling analysis is presented in Chapter 5. A list of publications and presentations to date, resulting from the present studies are listed in Chapter 6.

2. IGNITION OF PYROLYZATES, COAL AND CHAR

2.1. Purpose

The purpose of this task is to determine the effect of preheating on the ignition of coal and char particles. The flat flame burner with an opposed gas-particle jet will be used for these studies. Variables to be considered are the type of fuel, particle size, level of preheating, composition of carrier gas, temperature field and composition of oxidizing atmosphere.

2.2. Achievements

Two coals were selected for the studies. A sample of bituminous coal was obtained from Georgia Power Company. A sample of lignite (brown coal) was obtained from the U.S. Bureau of Mines, Liaison Office, North Dakota. Both coals were size graded into seven groups. The flat flame burner with the opposed gas-particle jet to be used for this task was modified and all flow measuring instrumentation and temperature probes were assembled.

Three particle feed systems were designed and built. One a screw type particle feeder provides high particle flow rates and can be used in association with large particles. The second particle feeder utilizes a fluidized bed and aspirator combination. The third particle feed systems uses only a fluidized bed arrangement. The last two particle feed systems provide low particle flow rates and they are best suitable for use with the small particles.

Burner characterization was carried out by recording temperature profiles using a Y-construction thermocouple. Variables considered during these measurements were combustible mixture, equivalence ratio, combustible mixture mass flow rate, carrier gas flow rate and composition, injection nozzle size, particle size and particle flow rate. A computer program was developed to translate the temperature profiles into isotherms and graphically display these isotherms.

For the studies reported herewith, two different size groups of particles were selected. Air and nitrogen were used as carrier gas for the particles in association with two different diameter opposed flow jets. Proximate analysis measurements were also conducted on the two types of coals.

2.3. Apparatus and Instrumentation

A flat-flame burner with an opposed gas-particle nozzle was designed, built and used to conduct investigations with metal particles [30-33]. This system was modified for use in the present study. The flow control and metering system was also modified to satisfy the needs of the investigation reported herewith. Detailed description of the flat-flame burner and associated instrumentation are summarized in Appendix A.

The flat-flame burner was coupled with three different particle feed systems. Initially a Metco Powder Feed Unit was modified and adapted with a screw type particle feed system. This particle feed system was found suitable for large particles and for high rate of flow of particles. In the present system this produced a high accumulation of particles on the flat-flame burner matrix. Two fluidized bed particle feed systems were then put into use. One of these two systems was coupled with an aspirator. Both of these systems were found suitable for low particle flow rates and they were also found suitable for use with small particles. All the results included in this report were obtained from experiments carried out in association with the two fluidized bed particle feed systems. Details on the particle feed systems are also included in Appendix A.

Associated with the flat flame burner instrumentation is a DISA traversing system used to traverse radially across the burner a Y-construction chromel-alumel thermocouple. This system then provided the capability to record on an X-Y plotter the radial temperature profiles at some fixed distance above the burner matrix.

A Thermolyne type 1400 furnace and a Mettler H51AR balance were used in proximate analysis measurements. A Pharr adiabatic calorimeter was used in heating value measurements on the fuels.

2.4. Experimental Procedure

Two coals, a bituminous and a lignite (brown coal) were ground and sized. Among the seven groups resulting the two with the smallest particle sizes were selected for the tests. Proximate analysis measurements were performed according to ASTM D3172-73 and associated standard procedures. Heating value determinations were also carried out following standard procedures.

Measurements concerning this task required the flat flame of the burner in association with the opposed gas particle jet. Consequently, the fuel and the air for the burner were turned on first, the combustible mixture ignited above the burner matrix and the necessary flow rates adjusted to establish a steady-state flame at the desired equivalence ratio and combustible mixture flow rate. Two different equivalence ratios of $\phi = 0.67$ and $\phi = 0.86$ were selected and the burner combustible methane-air mixture flow rates were varied from $\dot{m}_b = 1880$ g/h to $\dot{m}_b = 2430$ g/h.

Once the desired flat flame was established, the complementary systems of carrier gas and particle feed were activated and allowed to flow through one of the two jet nozzles. The two particle jet nozzle sizes used were 1.27 cm o.d. and 2.54 cm o.d. with carrier gases of either nitrogen or air. The carrier gas flow rate was varied from no flow to $\dot{m}_{cg} = 189$ g/h. The two coal particle size groups selected were < 53 μm and 53-74 μm with particle flow rates ranging from $\dot{m}_c = 6.6$ g/h to $\dot{m}_c = 28.2$ g/h. The gas-particle injection nozzle exit was placed both at 2 cm and at 3 cm above the top of the burner matrix.

Observations, temperature field measurements and photographic records were carried out as soon as all the desired variables were established. Some temperature measurements were taken along the axis of the nozzle. Others were made by traversing a chromel-alumel thermocouple across the flat flame burner and gas-particle jet system at various heights above the burner matrix from 0.3 cm to 4.3 cm.

Temperature profiles were thus recorded in the absence of any gas-particle flow through the nozzle, in the presence of only carrier gas flow through the nozzle and in the presence of a combined gas-particle flow through the nozzle.

Temperature measurements were also carried out using several different size thermocouples. These in turn were used to correct the temperature profiles measurements.

2.5. Results

2.5.1. Fuel Characterization

Two coals were selected for the studies presented in this report. A sample of bituminous coal was obtained from Georgia Power Company. A sample of lignite (brown coal) was obtained from the U.S. Bureau of Mines, Liaison Office, North Dakota. Both fuels were crushed and using screens they were size graded into seven groups. These groups are shown in Table 2.1. Among the seven groups the < 53 μm and the 53-74 μm groups were selected to conduct the tests with the existing system.

Table 2.1. Groups of Size Graded Coal Particles

Sieve No.	Screen Opening μm	Coal Size Range μm
40	420	297-420
50	297	210-297
70	210	149-210
100	149	105-149
140	105	74-105
200	74	53-74
270	53	<53

Proximate analyses and heating value determination were also carried out to further characterize the two types of coals used. The results of the proximate analysis measurements are presented in Table 2.2. The heating values of the coals, determined using an adiabatic calorimeter, are listed in Table 2.3. These represent higher heating values.

Table 2.2. Proximate Analysis of Coals

Fuel	Moisture %	Volatile %	Fixed Carbon %	Ash %
Brown Coal (<53 μm)	11.1	35.8	42.6	10.5
Brown Coal (53-74 μm)	11.9	34.9	43.2	10.0
Brown Coal (105-149 μm)	10.5	42.1	37.5	9.9
Bituminous Coal (<53 μm)	3.0	31.1	52.4	13.5
Bituminous Coal (53-74 μm)	2.8	32.1	51.7	13.4
Bituminous Coal (210-297 μm)	2.8	37.9	43.3	16.0

Table 2.3. Heating Values of Coals

Fuel	Heating Value J/g
Lignite (< 53 μm)	20,962
Bituminous (< 53 μm)	27,548

2.5.2. Burner Characterization

The burner characterization for the system consisted of establishing the various useful ranges available on the parameters. Although the flat-flame burner is capable in operating at both fuel lean and fuel rich mixture conditions for the present studies it was considered most suitable to use only fuel lean mixture. Thus excess air will be available for the particles entering the reaction zone from the nozzle. The selection of equivalence ratios of $\phi = 0.67$ and 0.86 was thus made. At the same time the combustible mixture flow rates were found to be most suitable between $\dot{m}_b = 1880$ g/h and 2460 g/h.

Carrier gas flow rate ranges were coupled primarily with the needed flow rates for the particle flow. For the ignition studies ranges of carrier gas up to $\dot{m}_{cg} = 190$ g/h were found to be most suitable. While in subsequent studies for sustained combustion these rates were substantially increased.

For the studies reported in this task, coal particle flow rates in the ranges between $\dot{m}_c = 6.6$ g/h and 28.2 g/h were found to be most suitable.

2.5.3. Gas Temperature Profiles and Isotherms

Temperature measurements were carried out both inside the gas-particle injection nozzle and in the reaction zone above the burner matrix and adjacent to the nozzle. The measurements were first carried out in the absence of any injection of gas and/or particles. Next only carrier gas was allowed to flow through the nozzle and the same temperature measurements were carried out. Finally, these temperature measurements were extended when the nozzle was used to inject into the reaction zone coal particles along with the carrier gas.

Axial temperature profiles within the gas-particle injection nozzle are presented in Figures 2.1 and 2.2. Additional axial temperature profiles in the nozzle are to be found in Appendix B as Figure B.1, B.2 and B.3. It is evident from these measurements that the addition of the carrier gas reduces the axial temperatures and these are further reduced with the addition of the particles in the flow. Exit temperatures are shown to range between 530°C and 640°C. Since

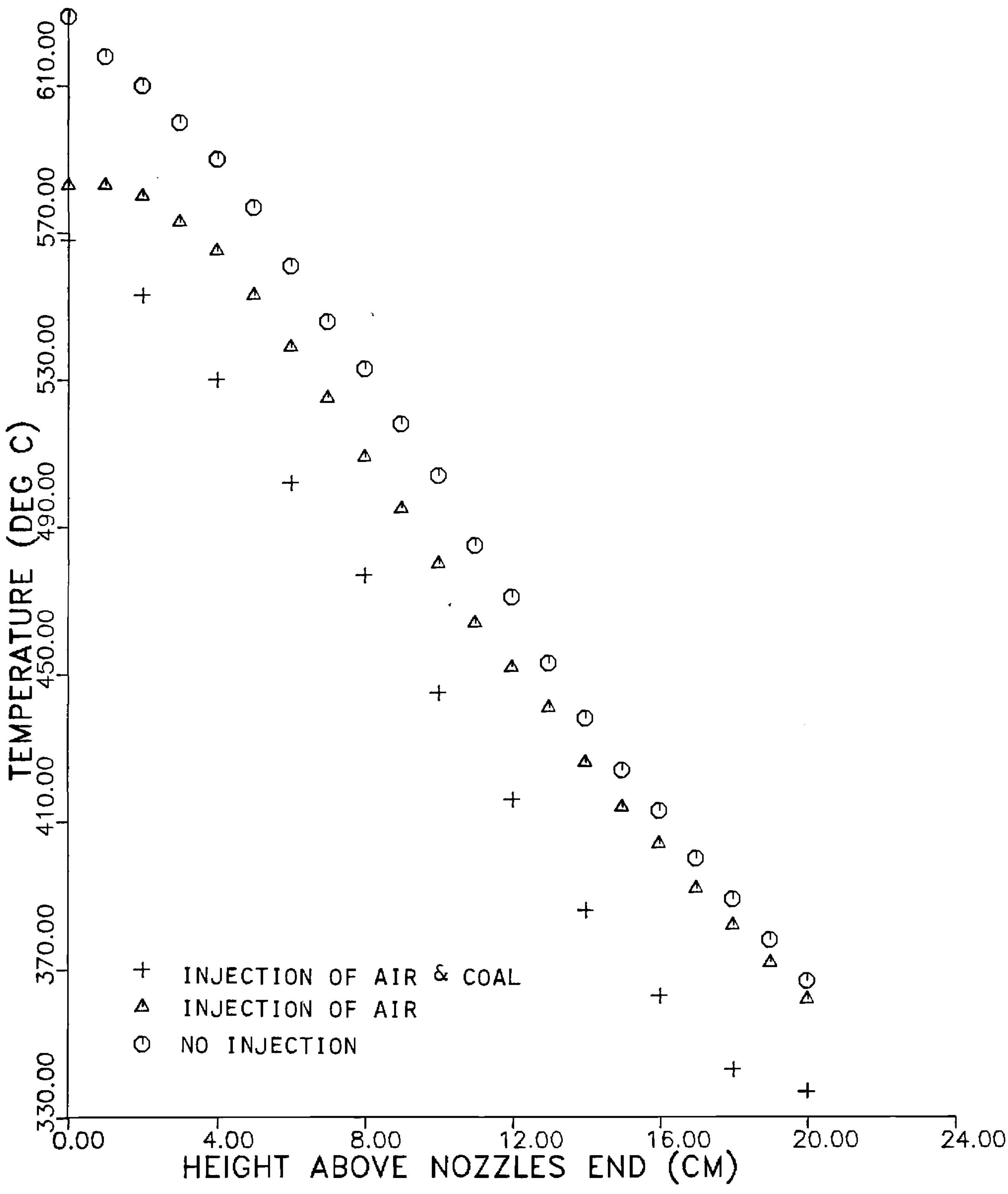


Figure 2.1. Axial Temperature Profiles Inside 1.27 o.d. Gas-Particle Nozzle of Flat Flame Burner, ϕ = 0.86, $\dot{m}_b$ = 2460 g/h, Air as Carrier Gas, $\dot{m}_{cg}$ = 54.6 g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c$ = 9.6 g/h.

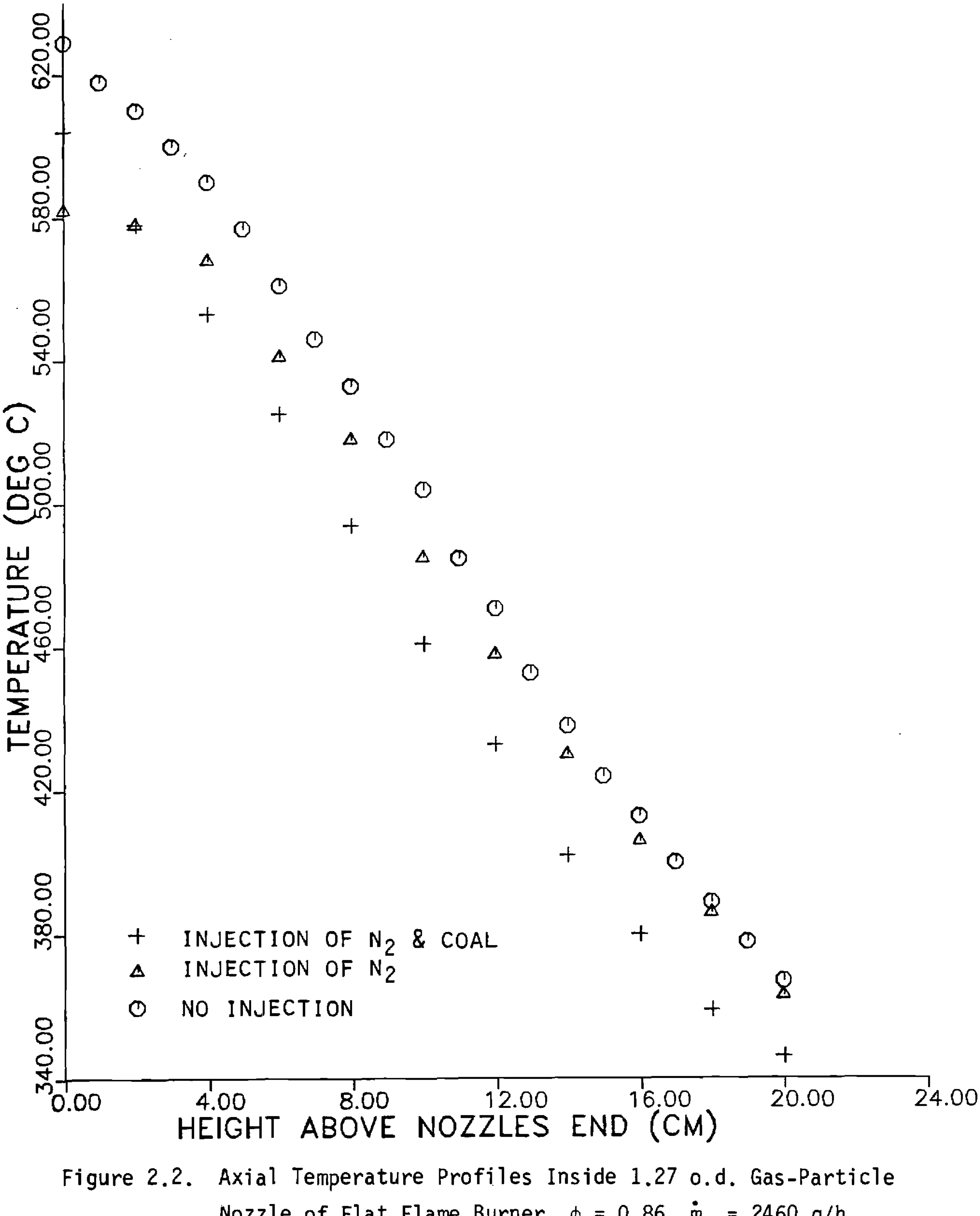


Figure 2.2. Axial Temperature Profiles Inside 1.27 o.d. Gas-Particle Nozzle of Flat Flame Burner, ϕ = 0.86, $\dot{m}_b$ = 2460 g/h, N_2 as Carrier Gas, $\dot{m}_{cg}$ = 53.6 g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c$ = 7.8 g/h.

the axial temperatures are the lowest temperatures within any horizontal plane in the nozzle then these measurements indicate that the present system provides temperatures near the exit of the nozzle which range around the self-ignition temperatures of the pyrolyzate gases.

Representative temperature profiles in the flat flame reaction zone above the burner matrix and adjacent to the gas-particle injection nozzle are shown in Figures 2.3 and 2.4. Additional temperature profiles have been included in Appendix B as Figures B.4-B.25 presenting different burner combustible mixture equivalent ratios, gas-particle injection nozzle size and taken at different heights above the burner matrix. All temperatures have been corrected for various losses. The correction values were determined from temperature measurements carried out with different size thermocouples. The reactive behavior of the coal particles can be followed through a sequence of these temperature profiles, appearing to be initiated shortly after the nozzle exit and intensifying as the particles move around the nozzle, ascending outside the nozzle and reach burn-out state.

A computer program has been developed to plot isotherms in the reaction zone of the flat flame burner. Once temperature profiles have been measured at various horizontal planes, for fixed system operating conditions these are first corrected for losses. The corrected temperatures are then fed to the computer and the resultant isotherm plots are produced. Representative isotherm plots for the 2.54 o.d. gas-particle injection nozzle as shown in Figures 2.5-2.10 for the burner equivalence ratios of $\phi = 0.67$ and 0.86. The isotherms represent qualitatively the effect of addition of coal particles in the reaction zone and their behavior. Isotherms for the 1.27 o.d. gas-particle injection nozzle have been included in Appendix B as Figures B.26-B.28. Figures 2.11 and B.29-B.31 are also for the 1.27 o.d. nozzle except that in these experiments N_2 was used as a carrier gas.

A comparison is made of the behavior of the two types of coal particles in Figures 2.12-2.14. All conditions were kept identical. On the same plots the temperature profiles under no injection and with injection of air only are included for reference. It is evident from

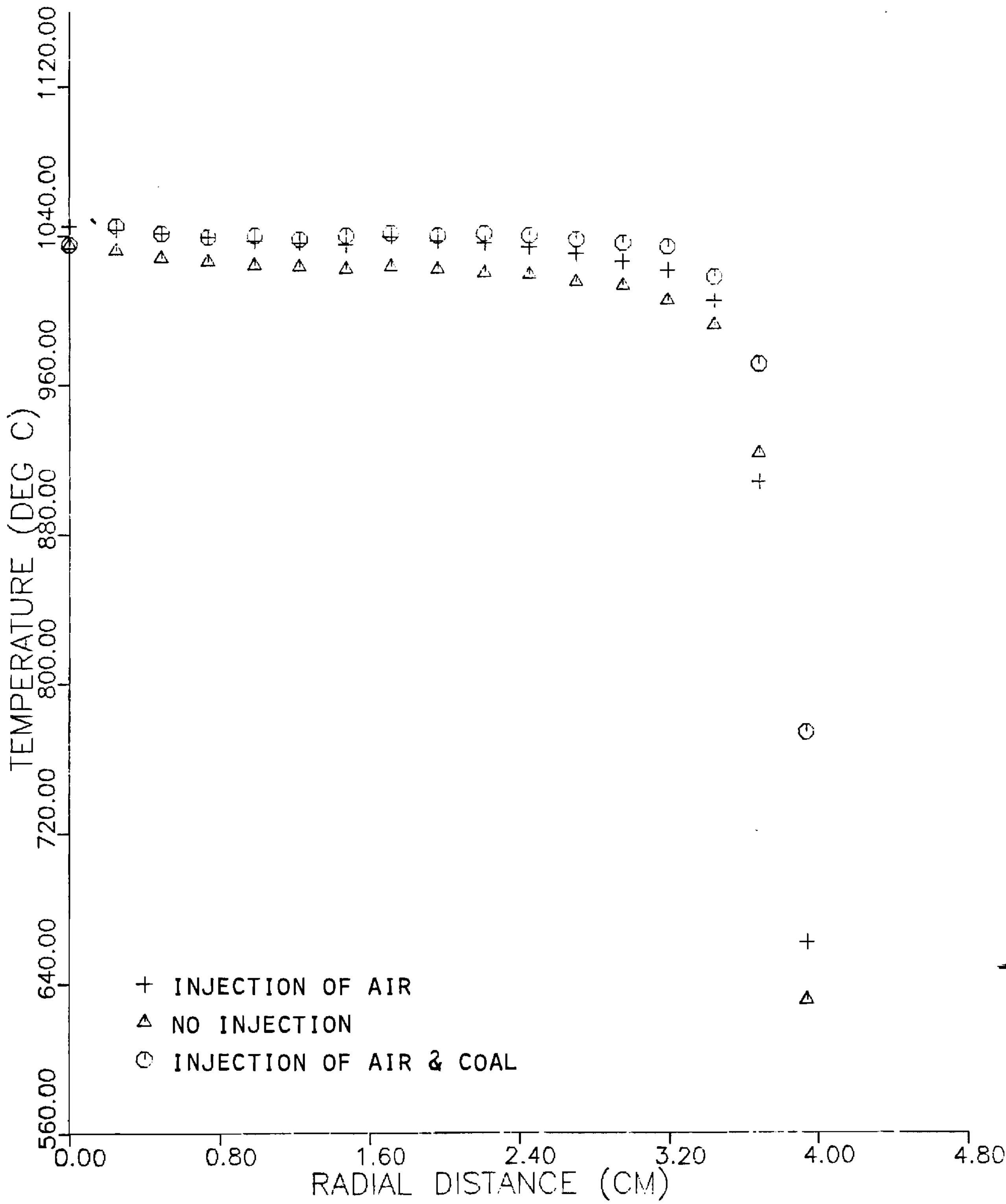


Figure 2.3. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg}$ = 189 g/h, Lignite Coal Particles 53-74 µm, $\dot{m}_c$ = 15.0 g/h, Height Above Burner Matrix H = 0.3 cm.

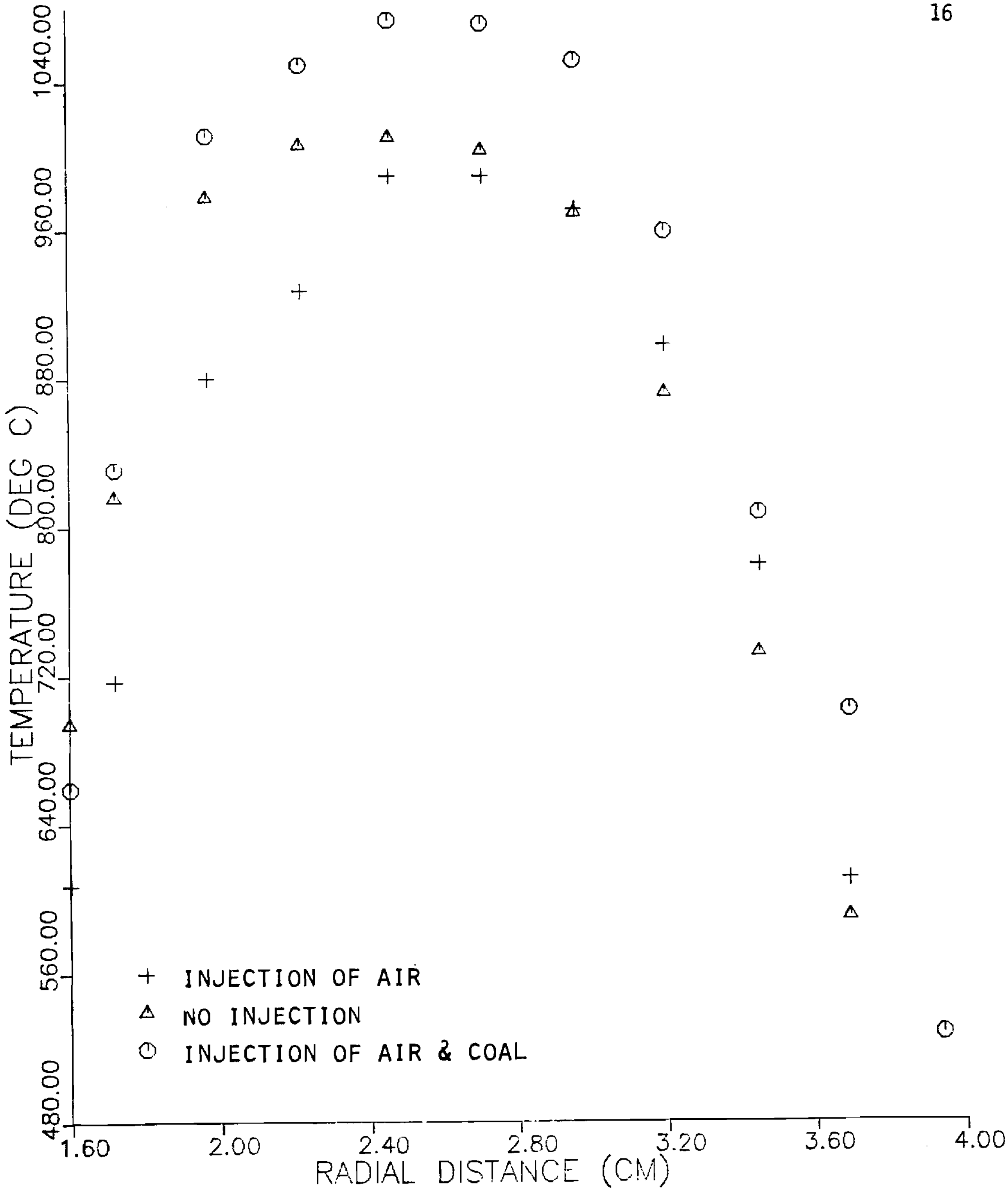


Figure 2.4. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 189$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 2.3 cm.

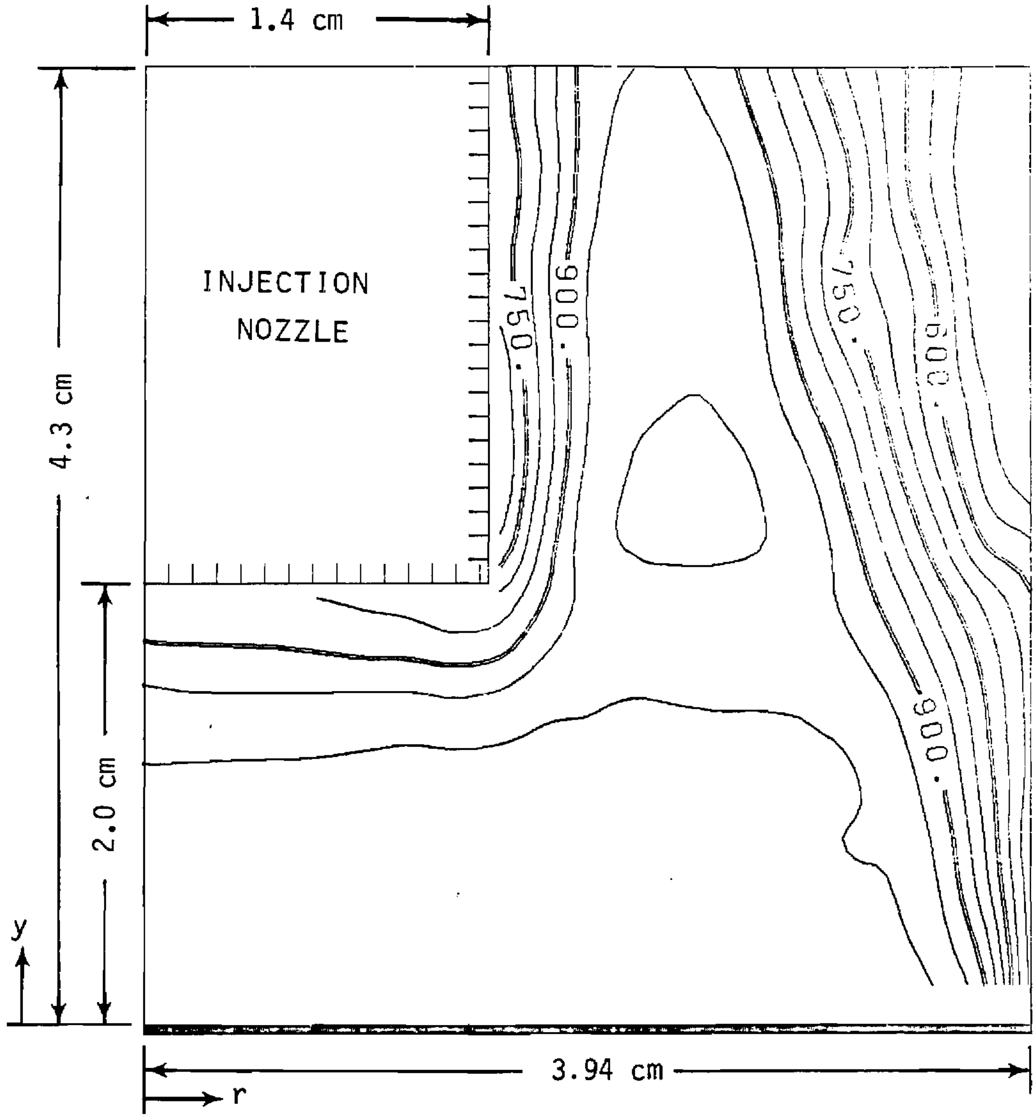


Figure 2.5. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, without Injection.

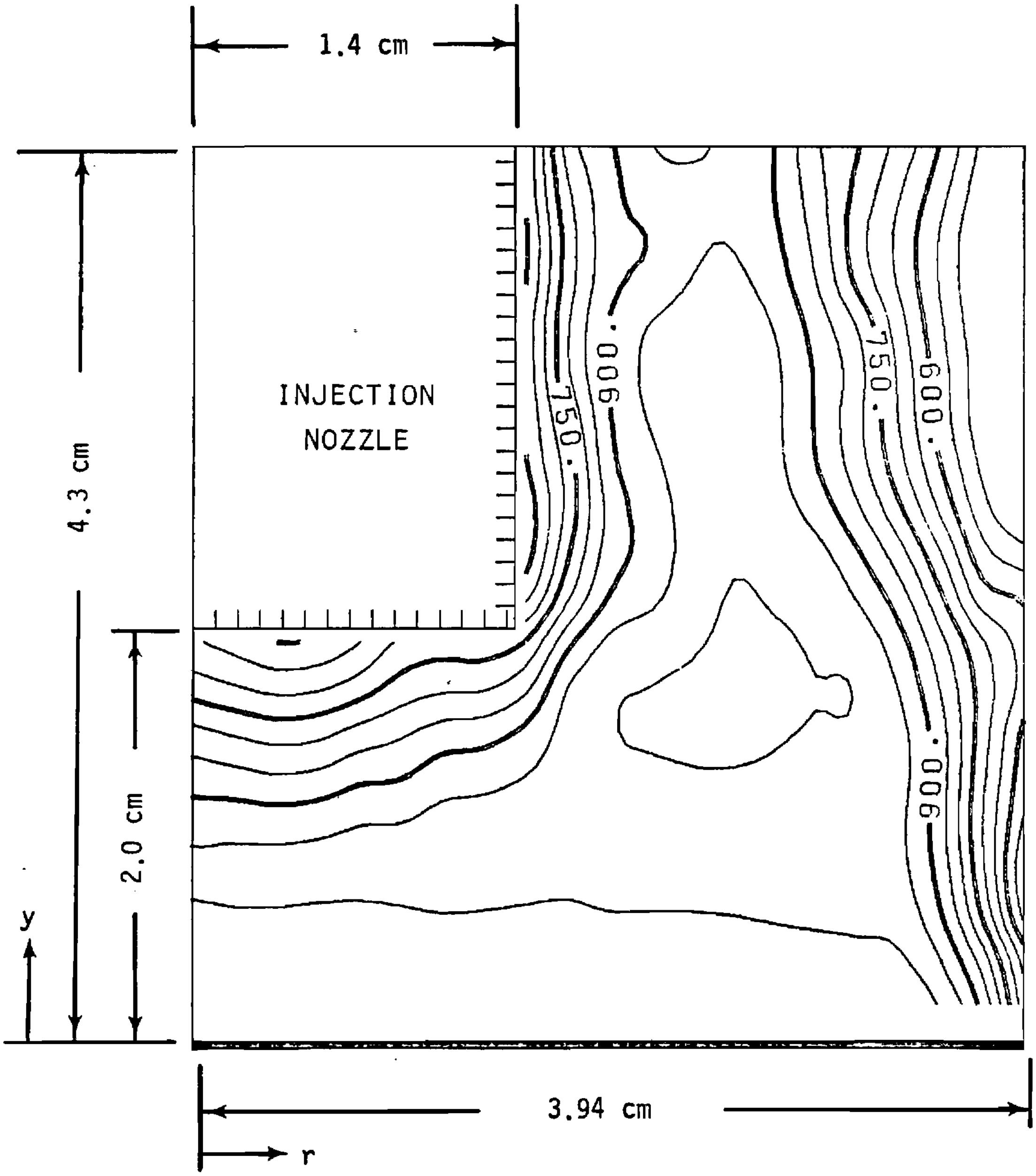


Figure 2.6. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, with Injection of Air, $\dot{m}_{cg}$ = 189 g/h.

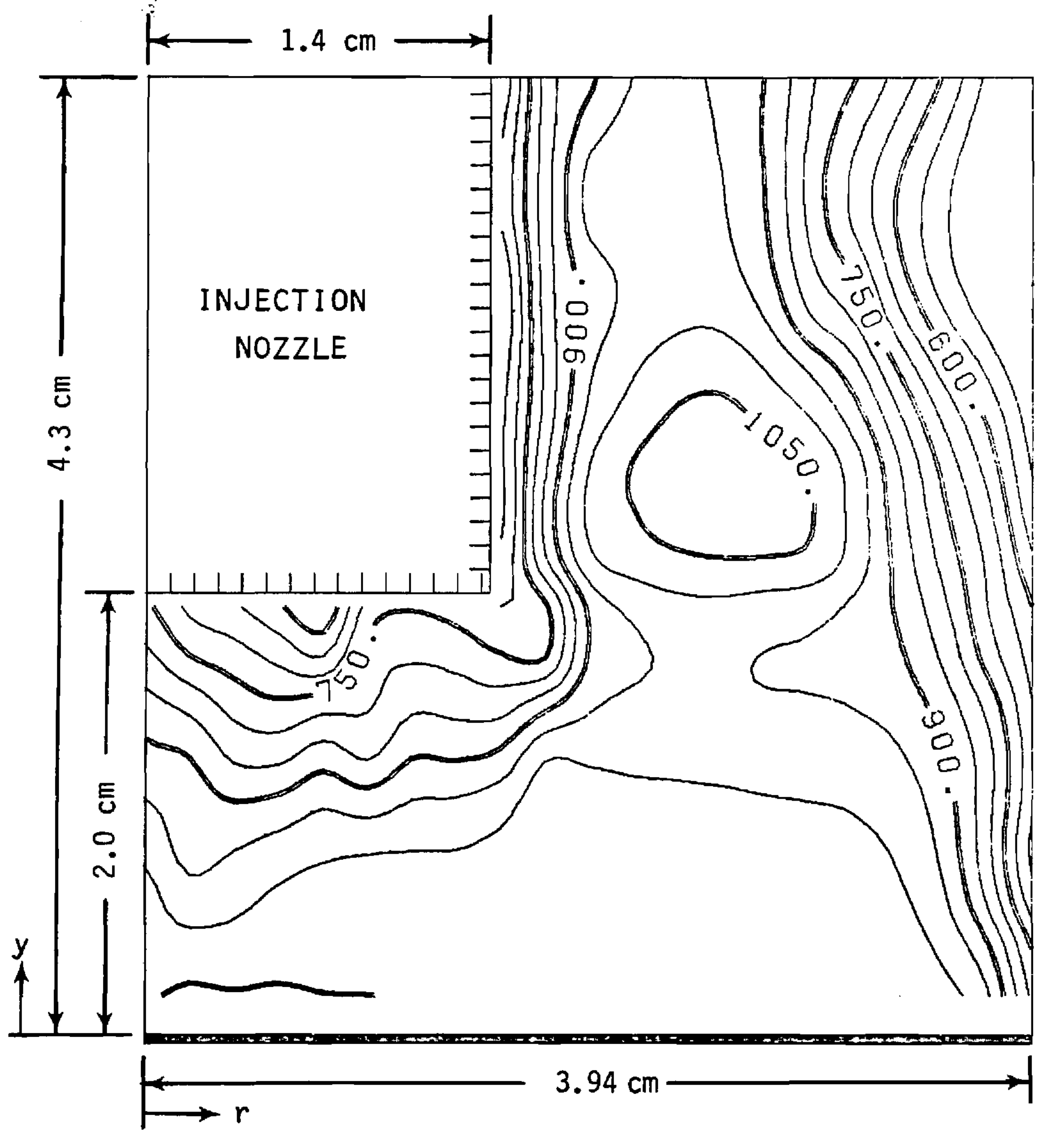


Figure 2.7. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, with Injection of Air, $\dot{m}_{cg}$ = 189 g/h, and Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 15.0 g/h.

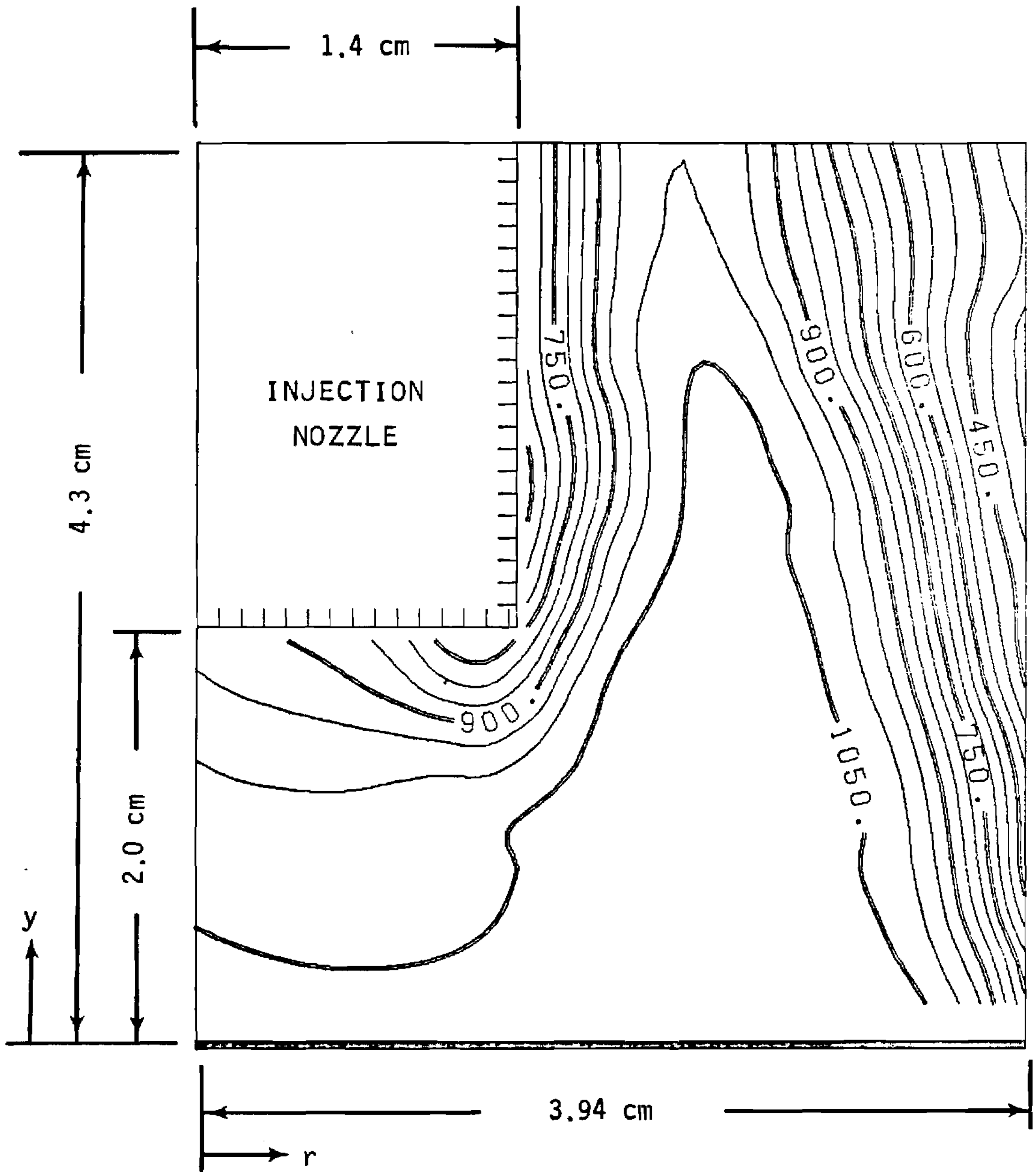


Figure 2.8. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2454 g/h, without Injection.

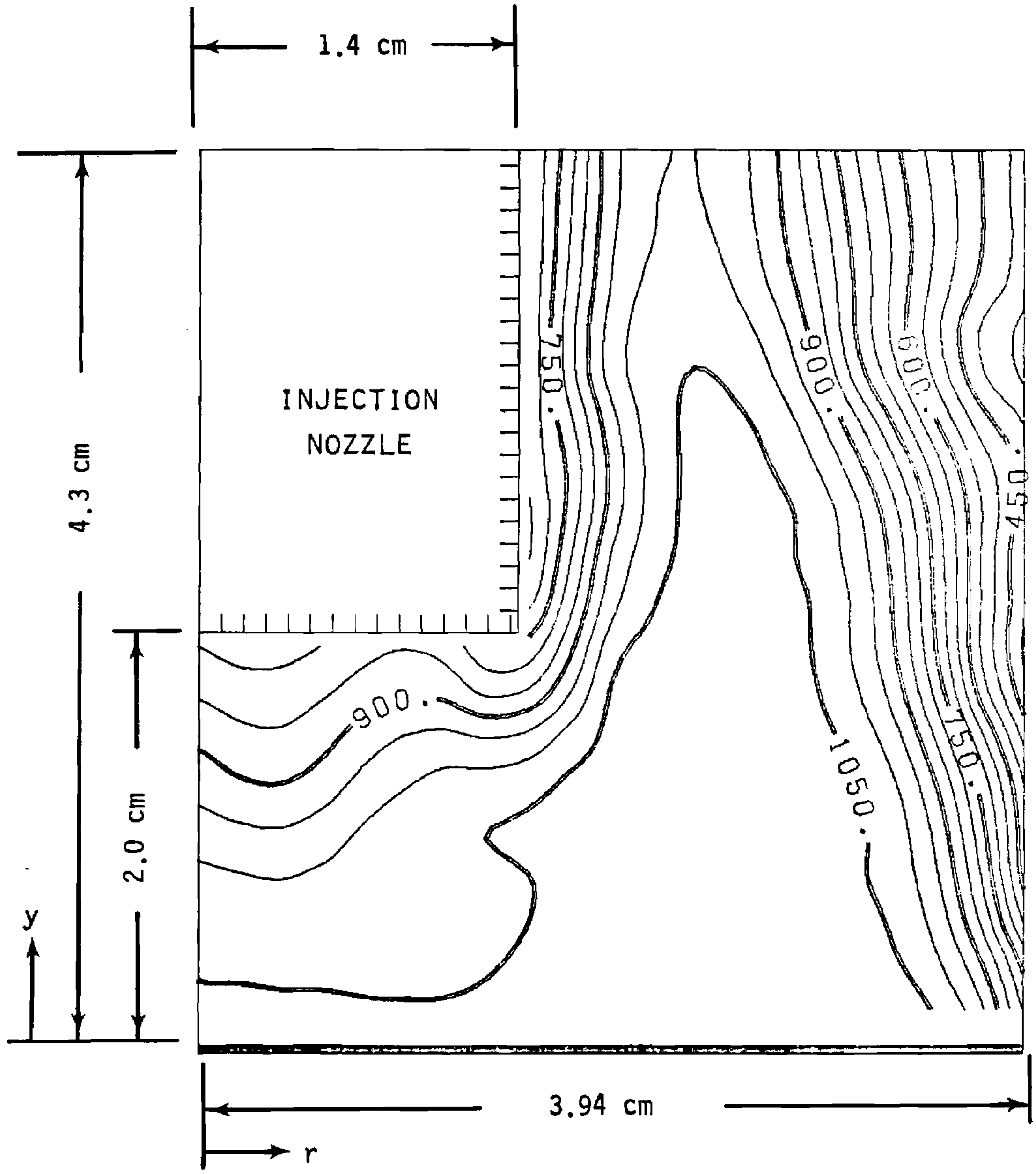


Figure 2.9. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2454 g/h, with Injection of Air, $\dot{m}_{cg}$ = 84.8 g/h.

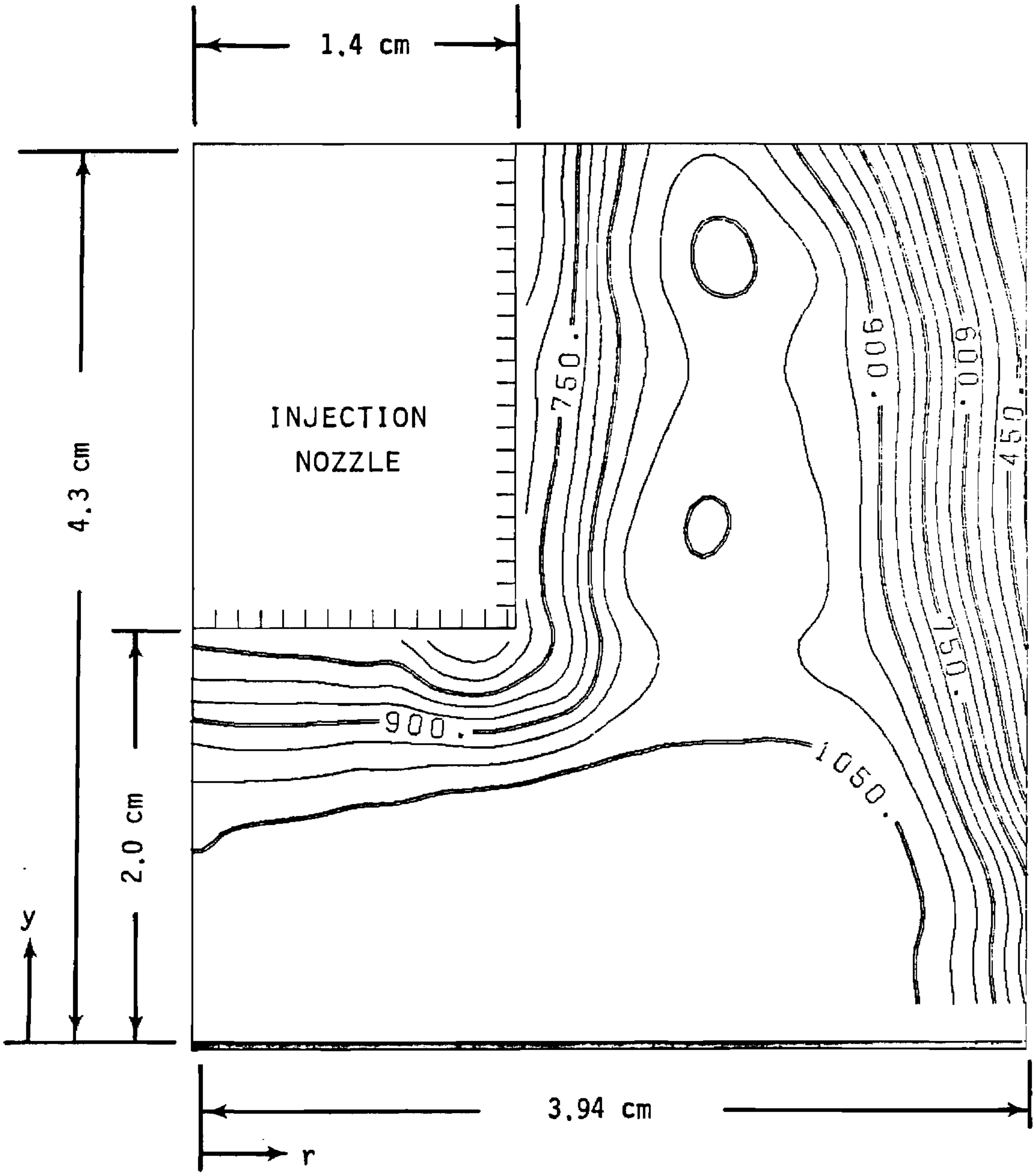


Figure 2.10. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2454 g/h, with Injection of Air, $\dot{m}_{cg}$ = 84.8 g/h, and Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 27.6 g/h.

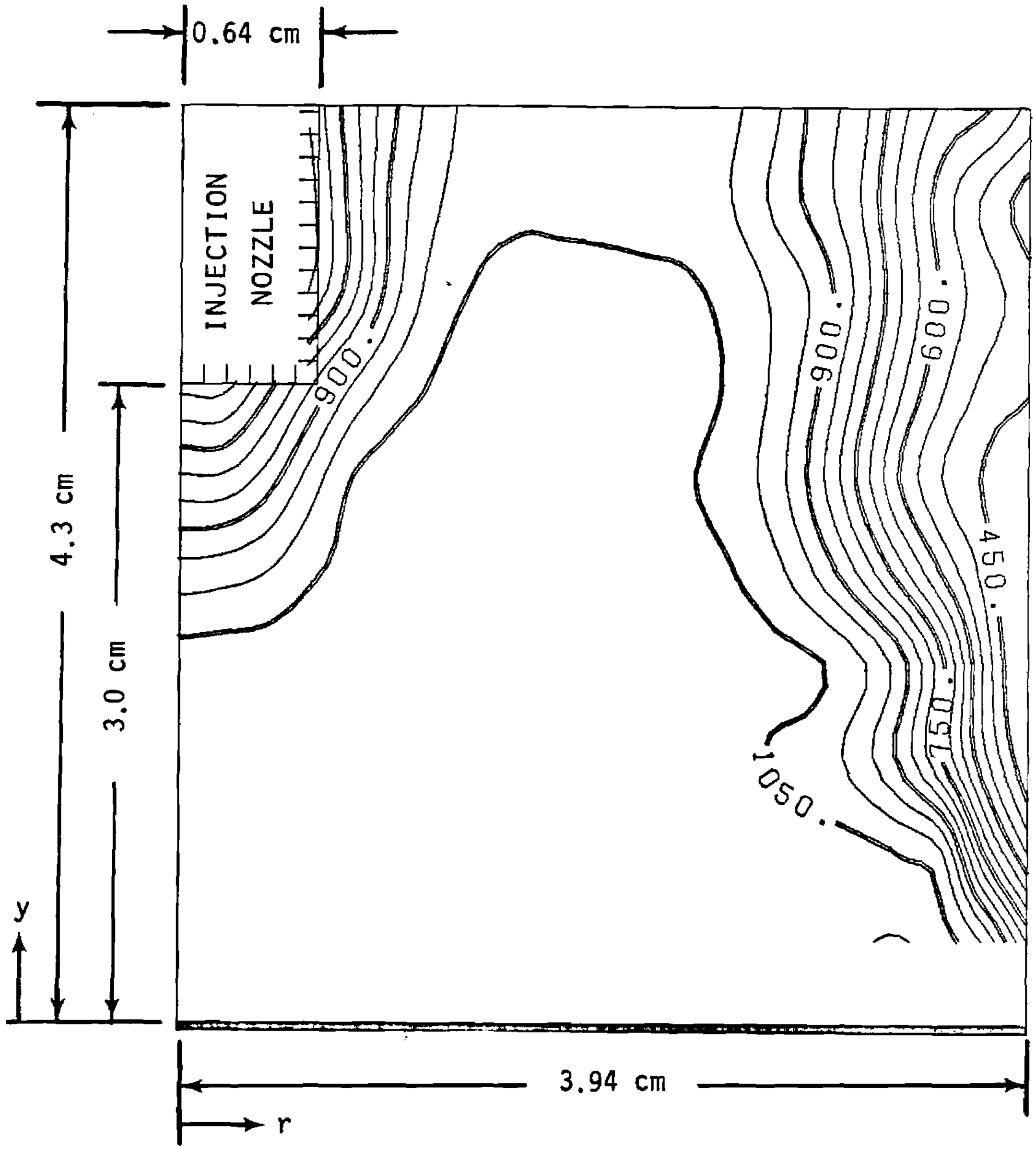


Figure 2.11. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2460 g/h, with Injection of Air, $\dot{m}_{cg}$ = 53.7 g/h, and Lignite Coal Particles 53-74 µm, $\dot{m}_c$ = 7.80 g/h.

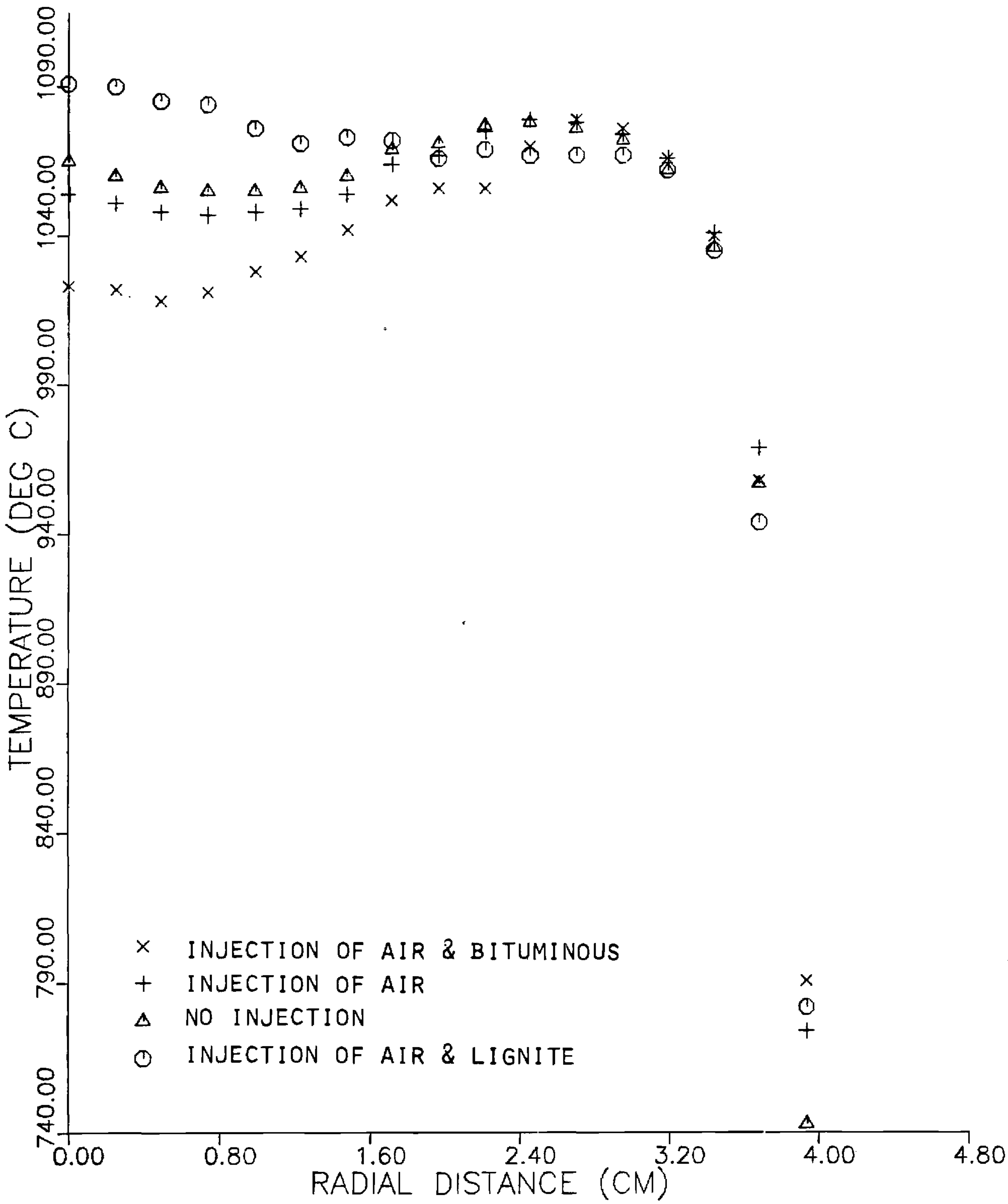


Figure 2.12. Comparative Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 2454$ g/h, 1.27 o.d. Gas-Particle Injection Nozzle, $\dot{m}_{cg} = 84.8$ g/h, 53-74 μm Coal Particles, $\dot{m}_c = 28.6$ g/h, Height Above Burner Matrix H = 0.3 cm.

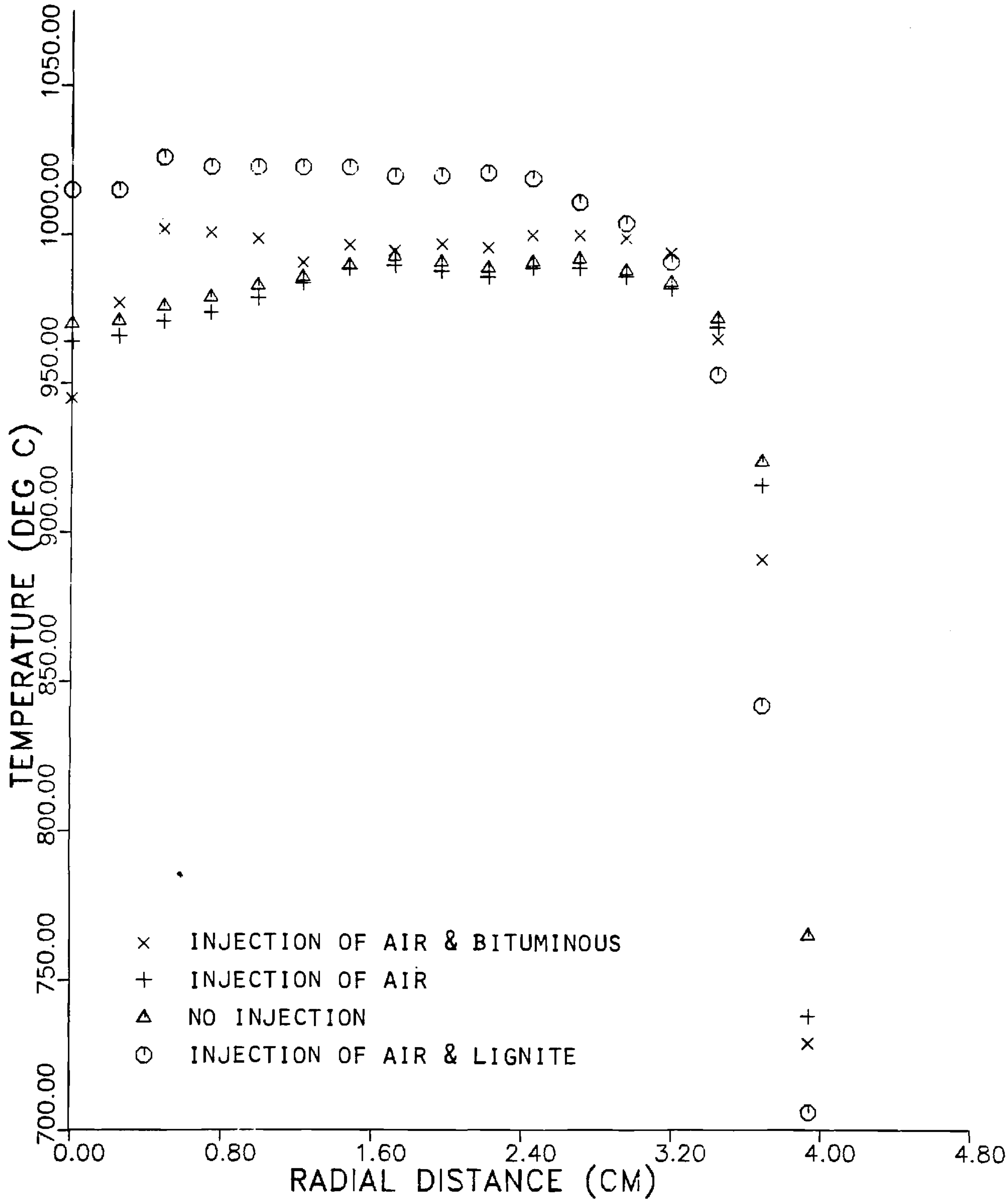


Figure 2.13. Comparative Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.86, $\dot{m}_b$ = 1883 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, $\dot{m}_{cg}$ = 38.4 g/h, 53-74 μm Coal Particles, $\dot{m}_c$ = 6.6 g/h, Height Above Burner Matrix H = 0.2 cm.

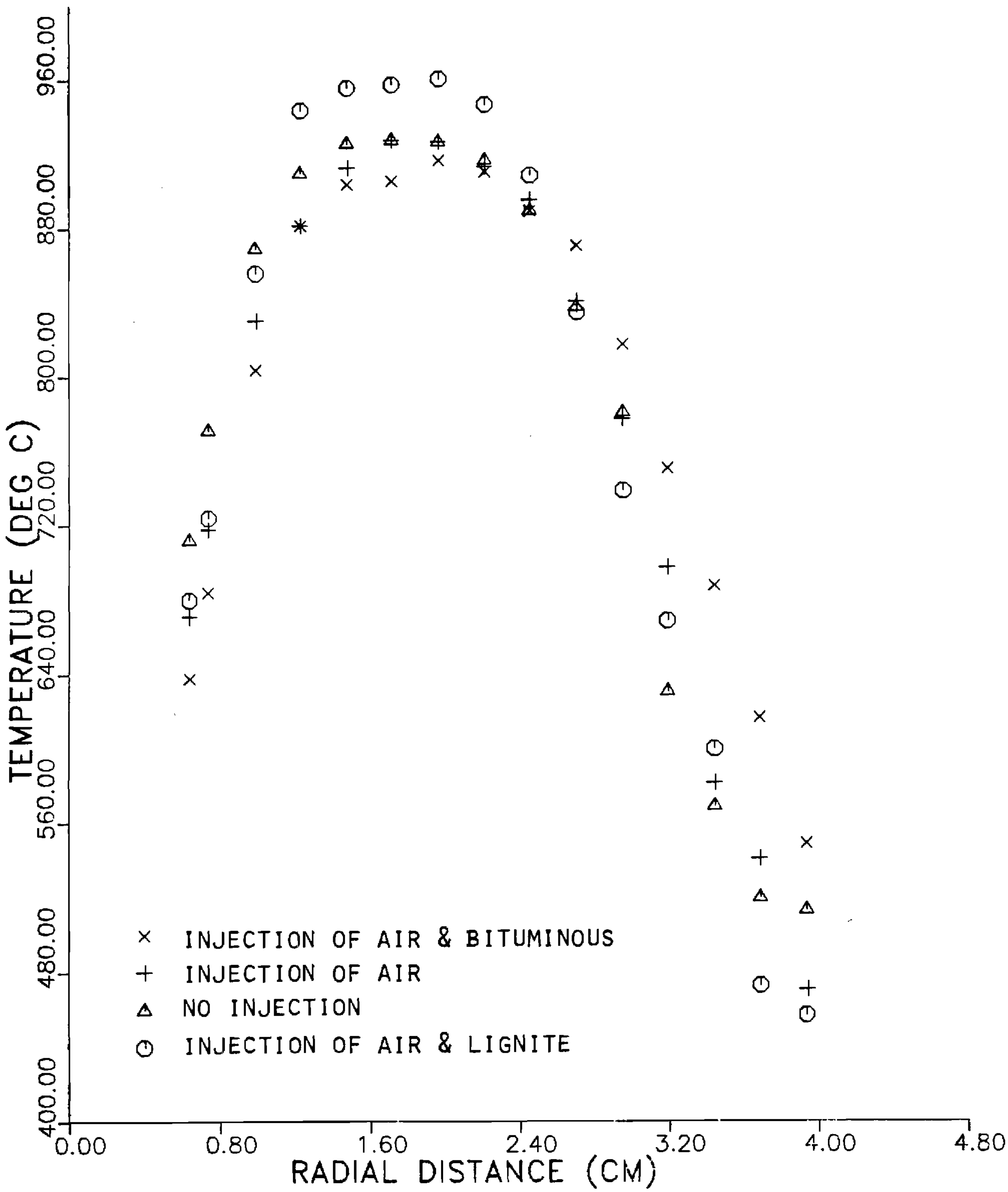


Figure 2.14. Comparative Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 1883$ g/h, 1.27 o.d. Gas-Particle Injection Nozzle, $\dot{m}_{cg} = 38.4$ g/h, 53–74 μm Coal Particles, $\dot{m}_c = 6.6$ g/h, Height Above Burner Matrix H = 2.8 cm.

these measurements that the bituminous coal particles are slower in achieving an exothermic reactive level and consequently ignition.

As indicated by the figures presented in this section and in the appendix as well as other measurements, the temperatures around the exit of the nozzle are lower with the presence of particles. This decrease in temperature was found to be as much as 250°C. At the same time a temperature rise occurs in the stream flowing outside the nozzle and the temperature rises were found to reach up to 100°C.

2.5.4. Observations

Visual observations with both bituminous and lignite and particles have shown some distinct behavior. With air as a carrier gas most of the lignite particles were found to ignite in the injection tube before their exit. The ignition appeared to be in the gas phase and was followed by the combustion of the volatiles forming a flame tube as they moved upwards outside the injection nozzle. This was followed by the burning of the char. In contrast, bituminous particle ignition under the same conditions appeared to occur almost always outside the injection nozzle which indicates that they required a higher ignition temperature. The reaction was followed by a fast expulsion of volatiles forming a flame sheet below the nozzle.

2.6. Conclusions

The preliminary studies carried out with the flat flame burner and the opposed gas-particle jet have shown the feasibility of studying the ignition of pyrolyzate and coal particles. These were found to be affected by the level of preheating, composition of carrier gas and type of fuel particle. The behavior of lignite particles compared to bituminous particles were found to be distinctly different. Under the range of conditions used in the present study lignite was found to be more suitable to use with regenerative pyrolysis. This work at the same time has shown the need to expand the study and use additional instrumentation to further quantify the behavior of these coal particles under regenerative pyrolysis conditions.

3. PYROLYSIS OF COAL

3.1. Purpose

The purpose of the coal pyrolysis investigation is to study the effect of initial atmosphere and heating rate during pyrolysis on the composition and ignition characteristics of pyrolysis gases. The pyrolysis apparatus known as the Lower Ignition Temperature and Concentration Apparatus (LITACA), which has been used in pyrolysis studies of cellulosic and thermoplastic materials [22], was modified for use with coal. The pyrolysis study focused on the degree of pyrolysis as a function of type of fuel, initial atmosphere and rate of heating during pyrolysis. The pyrolysis gas characteristics were classified in terms of minimum ignition temperature of these gases as a function of pyrolyzate-air concentration, flammability limits and apparent molecular weight of pyrolysis gases.

3.2. Achievements

Minor modifications were carried out on the Lower Ignition Temperature and Concentration Apparatus (LITACA). To test the reaction cell and establish procedures for ignition tests through the reaction cell with gaseous fuels, a total of 62 ignition runs were carried out with methane (CH_4), propane (C_3H_8) and butane (C_4H_{10}).

Using bituminous and lignite (brown) coal particles that have been sized into the groups of < 62 μm and 149-247 μm the total of twenty pyrolysis runs were carried out at three heating rates and with seven different initial atmospheres in the sample tube of the furnace. From each pyrolysis run at least one gas sample was drawn to determine the apparent molecular weight of the generated gaseous fuel. The remainder of the pyrolyzate gases were used to conduct the total of 117 ignition temperature measurements at various air-fuel concentrations.

Electronmicrographs were obtained from a few samples of the coal particles and of the residual chars after pyrolysis. In addition to the proximate analysis carried out on the coals and reported in Chapter 2, proximate analyses were also performed on some of the residual chars.

3.3. Apparatus and Instrumentation

The Lower Ignition Temperature and Concentration Apparatus (LITACA) has been designed, built and modified to pyrolyze cellulosic fabrics, thermoplastic fabrics and biomass fuels [22,34-37]. The pryolyzate gases from these materials were generated at heating rates from 20 to 6000°C/min and their ignition characteristics determined. The apparatus has been used for the current studies on coal pyrolysis with only minor modifications. Detailed description of LITACA and associated instrumentation together with the modifications are presented in Appendix C.

3.4. Experimental Procedure

3.4.1. Pyrolysis

The minimum self-ignition temperature measurements on pyrolyzate-air mixtures require that the material being tested must first be pyrolyzed and then the gaseous products must be stored until they are ready to be used for the self-ignition temperature tests. For each pyrolysis run approximately a 25 gram of coal sample was used. It was then loosely placed on the stainless steel screen and inserted into the sample holder tube. The sample tube was then placed in the furnace and properly attached to the system.

Before initiating the pyrolysis of the sample materials, all guard heaters were turned on and adjusted to maintain a temperature of about 120-140°C. Then the system vacuum pump was turned on and a vacuum of approximately 10^{-1} μm Hg was drawn on the system. The vacuum pump was then turned off to check the system for leaks. If after a period no loss in vacuum was observed the system was flushed with nitrogen or air and evacuated twice before a final pressure was established for the pyrolysis runs with the appropriate gas.

The pyrolysis runs conducted with the radiant heater furnace included a preheat period. The preheat auto-transformer of the radiant heating furnace was, therefore, set to provide a temperature of 140-150°C in the furnace when the heating cycle would be initiated. This same transformer controlled also the postheat temperature in the furnace. The furnace auto-transformer was adjusted to provide the desired voltage and heating rate during pyrolysis. For the tests reported here, it was selected to carry all pyrolysis runs to completion. The preheat period was of about two minute duration for all pyrolysis runs and it normally took between 17 minutes and 25 minutes to complete the pyrolysis process depending on the selected pyrolysis heating rate.

During the pyrolysis runs the top of the accumulator piston was vented to the atmosphere and consequently the volume expanded once the pressure in the system exceeded one atmosphere. When the pyrolysis process was completed, the piston vent valve was closed and the top of the accumulator piston was pressurized with nitrogen to provide a pressure in the accumulator of about 50 cm Hg gauge.

3.4.2. Self-Ignition Temperature Measurements

The minimum self-ignition temperature measurements were initiated by turning on the air and the air flowmeter adjusted to provide the desired level of flow. Next, the preignition heater and the ignition heater auto-transformers were turned on. Finally, the gas fuel valve was turned on and the flowmeter valve adjusted to provide the desired level of flow.

The three thermocouples in the ignition tube (see Section C.7 in Appendix) were used to continuously record the temperature of the gases on the strip chart recorders. By monitoring the temperature history of the fuel-air mixture flowing through the ignition tube, the minimum self-ignition temperature can be determined. In the latter experiments the ignition temperature detection system was modified to enhance the detection of the onset of ignition. A fourth thermocouple placed outside the ignition tube and in level with the middle thermocouple was used to detect the heating rate in a non-reactive environment. Thus, the thermocouple just outside the flow tube gives a reference temperature value to compare with the temperatures inside the tube. The difference between the inside temperatures and the reference value yields measurements of increased sensitivity. As soon as ignition was detected, all pertinent data was recorded, the pyrolyzate flow was turned off, all reaction cell heaters were turned off, and the air flow was turned on full to purge the ignition tube and cool the reaction cell.

If ignition did not occur by the time the maximum temperature thermocouple reached 1000°C, the test was terminated. The reaction cell heaters and the fuel supply were turned off.

3.4.3. Molecular Weight Measurements

Before initiating the pyrolysis in the furnace sample tube preparations were carried out for the molecular weight measurements. These consisted of turning on the oven, evacuating the balloons and after weighing them, placing them in the oven. Once the pyrolysis process was completed, one of the balloons was used to draw the pyrolyzate gases in the evacuated balloon and the balloon returned to the oven. When the balloon established a thermal equilibrium with the oven, the balloon petcock was opened to depressurize it and allow it to reach pressure equilibrium with the atmosphere. The balloon full of pyrolyzate gas was then weighed and using the tare weight of the balloon the net weight of the pyrolyzate gas was established.

3.5. Results

3.5.1. Coal Pyrolysis

Bituminous and lignite (brown) coals were ground and sized. For the tests reported here two groups of particles were used for the pyrolysis tests. Most of the tests were carried out with coal particles less than 62 μm and some tests were carried out with coal particles in the range of 149-247 μm. Initial heating rates of 2570°C/min, 4340°C/min, and 6460°C/min were used for the pyrolysis of coal and these represent available power to the furnace tungsten filament infrared lamps of 5 W/cm^2, 10 W/cm^2, and 15 W/cm^2, respectively for the 25.4 cm length. The initial heating rates (Figure 3.1) were obtained using a blackened chromel-alumel thermocouple placed in a stagnant nitrogen atmosphere of the quartz sample holder tube and exposed to the infrared lamps. These heating rates are comparable to those

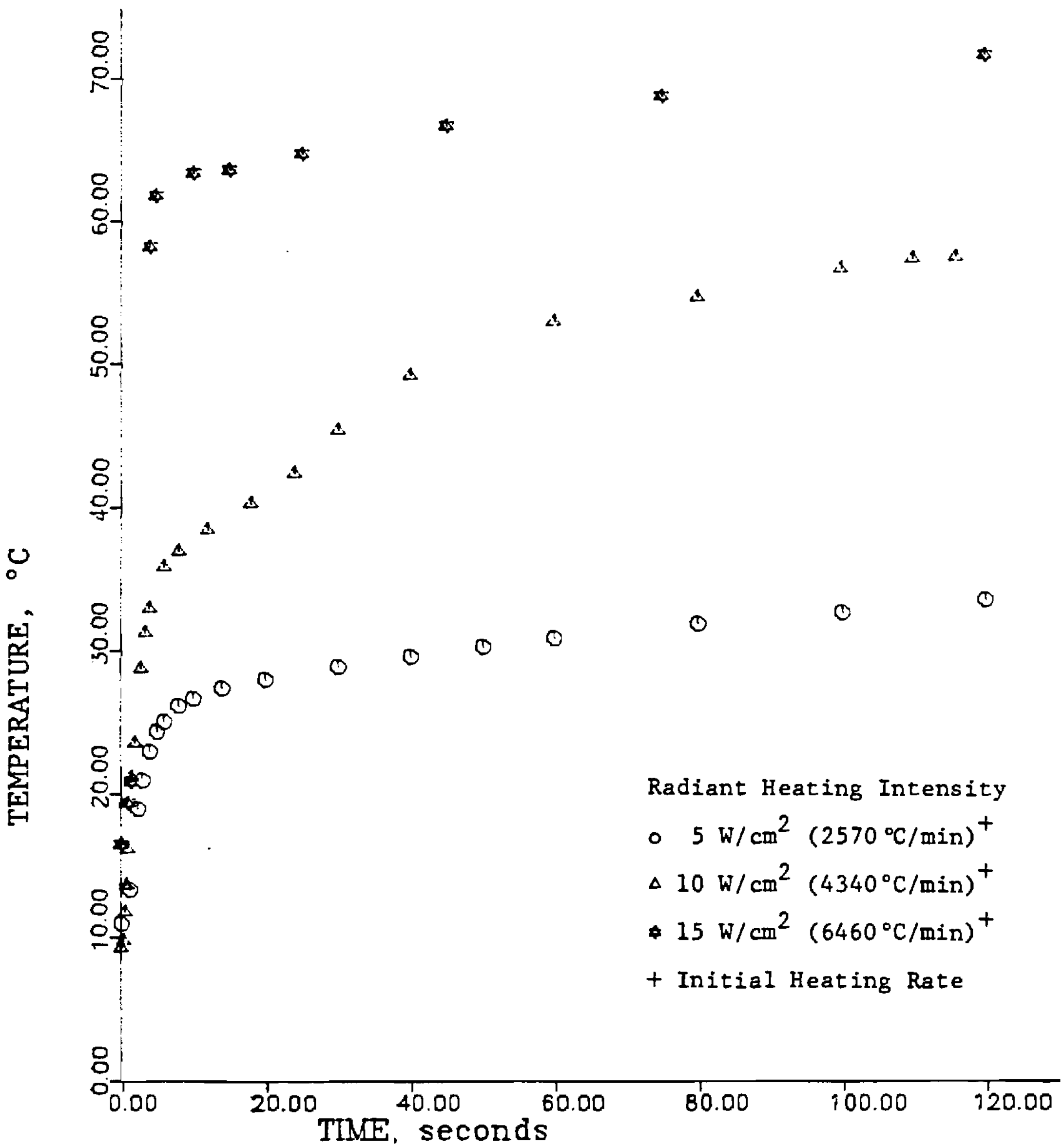


Figure 3.1. Pyrolysis Heating Rate Curves for LITACA Pyrolysis Furnace with a Blackened Chromel-Alumel Thermocouple in a Stagnant N_2 Atmosphere.

encountered by particles flowing down a jet in opposed flow with a flat burner (see Section 5.3. Model Simplifications and Parameter Ranges). An initial atmosphere of trace N_2, trace air, 17-74 cm Hg nitrogen and 22-46 cm Hg air were also used as a variable in the coal pyrolysis studies. Proximate analyses were performed on the pyrolyzed coal residues and compared with the proximate analyses of the unpyrolyzed coals.

3.5.2. Self-Ignition Temperatures

The minimum self-ignition temperatures were determined from the temperature history of the fuel-air mixture flowing through the ignition tube. A representative set of curves shown in Figure 3.2, identifies the changes in the slope of the temperature curves and specifies the ignition point. A second type of temperature curve was also observed where the initial exothermicity was closely followed by an endothermicity. This type of behavior was designated as a quenching reaction (QR) and a representative curve is presented in Figure 3.3. With the addition of the fourth thermocouple, four thermocouple history curves were recorded as shown in Figure 3.4. However, with this arrangement the minimum self-ignition temperature for a given fuel-air ratio is found by observing an increase in the temperature difference curves shown in Figure 3.5. This technique increased the sensitivity of identification of the ignition temperature. Corresponding temperature histories for the four thermocouples under quenching reaction conditions are shown in Figure 3.6. Temperature difference curves for this ignition measurement are shown in Figure 3.7.

The results of minimum self-ignition measurements on pyrolyzate gases generated from bituminous coals at various conditions are presented in Figure 3.8. On the same figure two lines are drawn which bracket the major group of the points. In the fuel lean region the ignition temperature range is narrow with as little as 17°C difference at some Y_F value while it widens to reach about 400°C as the fuel rich limit is approached. Thus the minimum ignition temperatures in the fuel lean region appear to be independent of the variables considered.

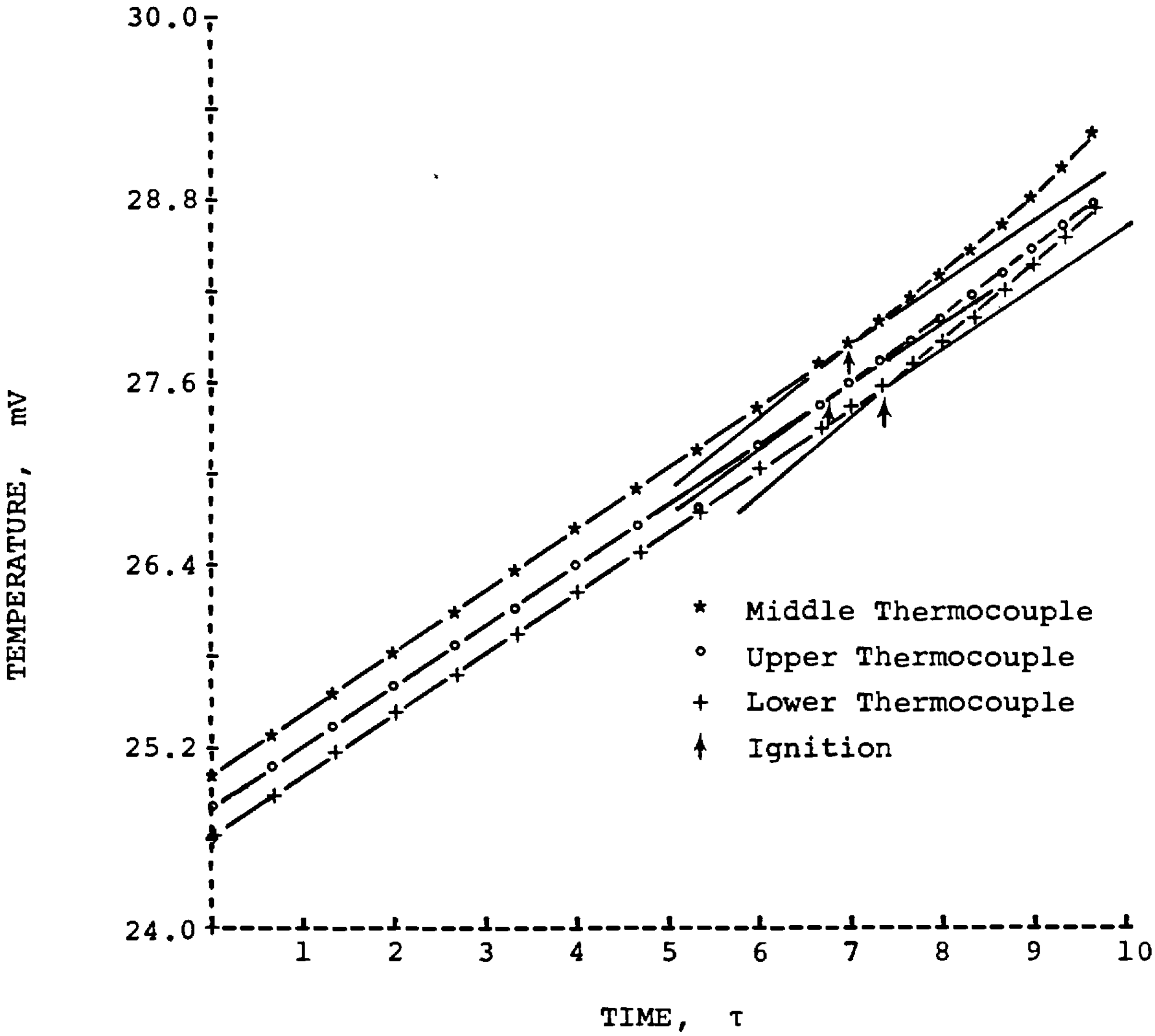


Figure 3.2. Detection of Pyrolyzate Ignition

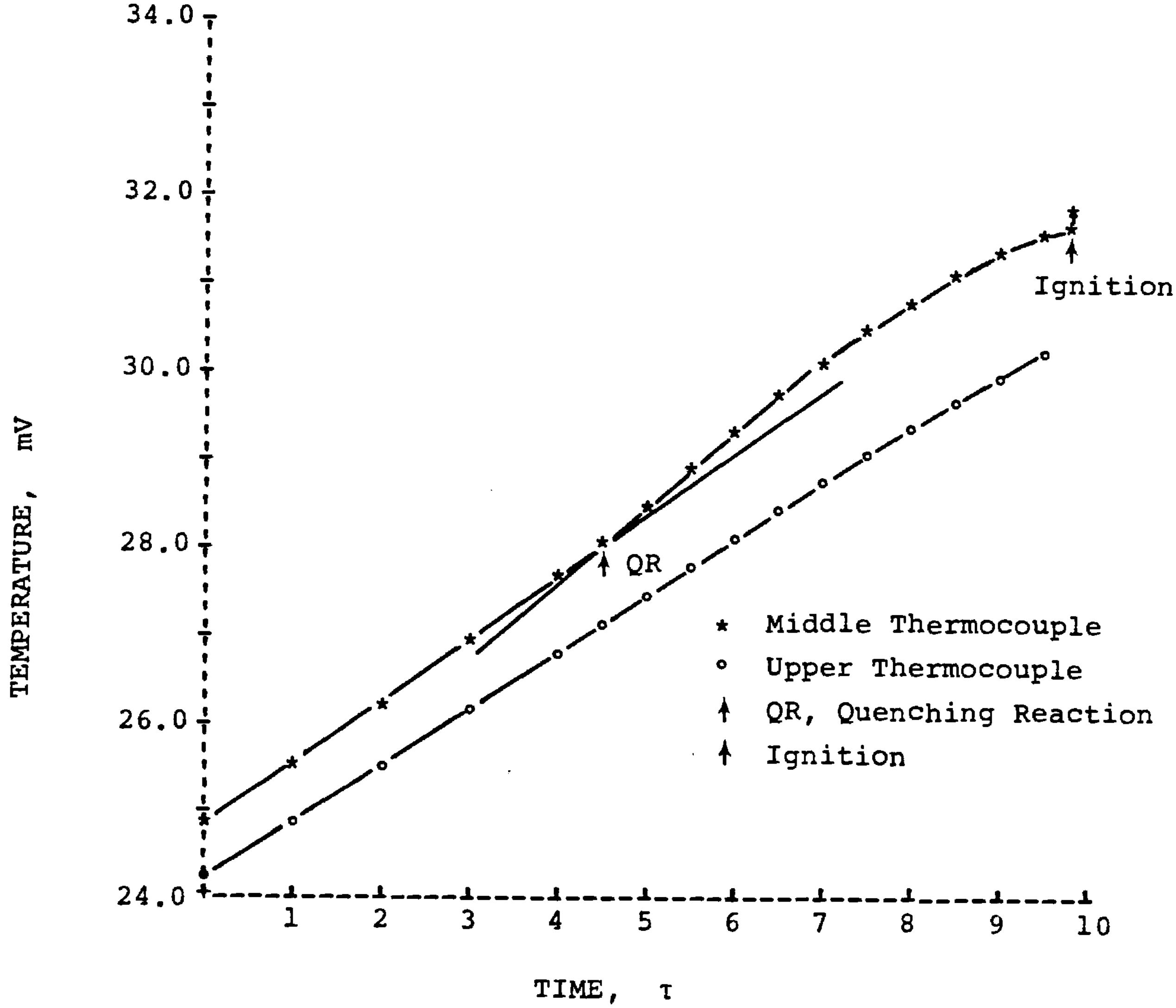


Figure 3.3. Detection of a Quenching Reaction
Followed by Ignition.

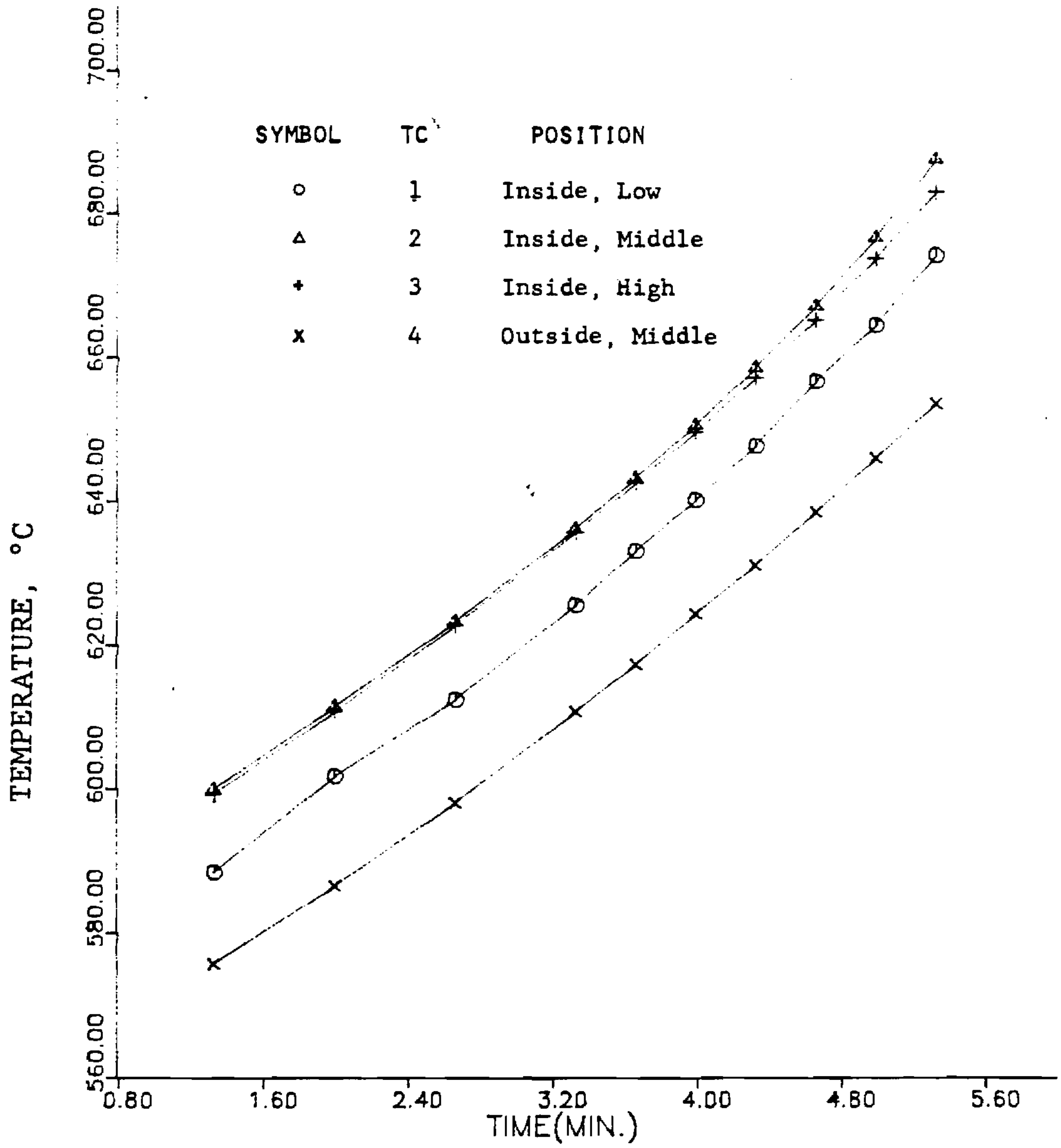


Figure 3.4. Typical Temperature Histories for the Reaction Cell Thermocouples, Showing the Onset of Pyrolyzate Ignition.

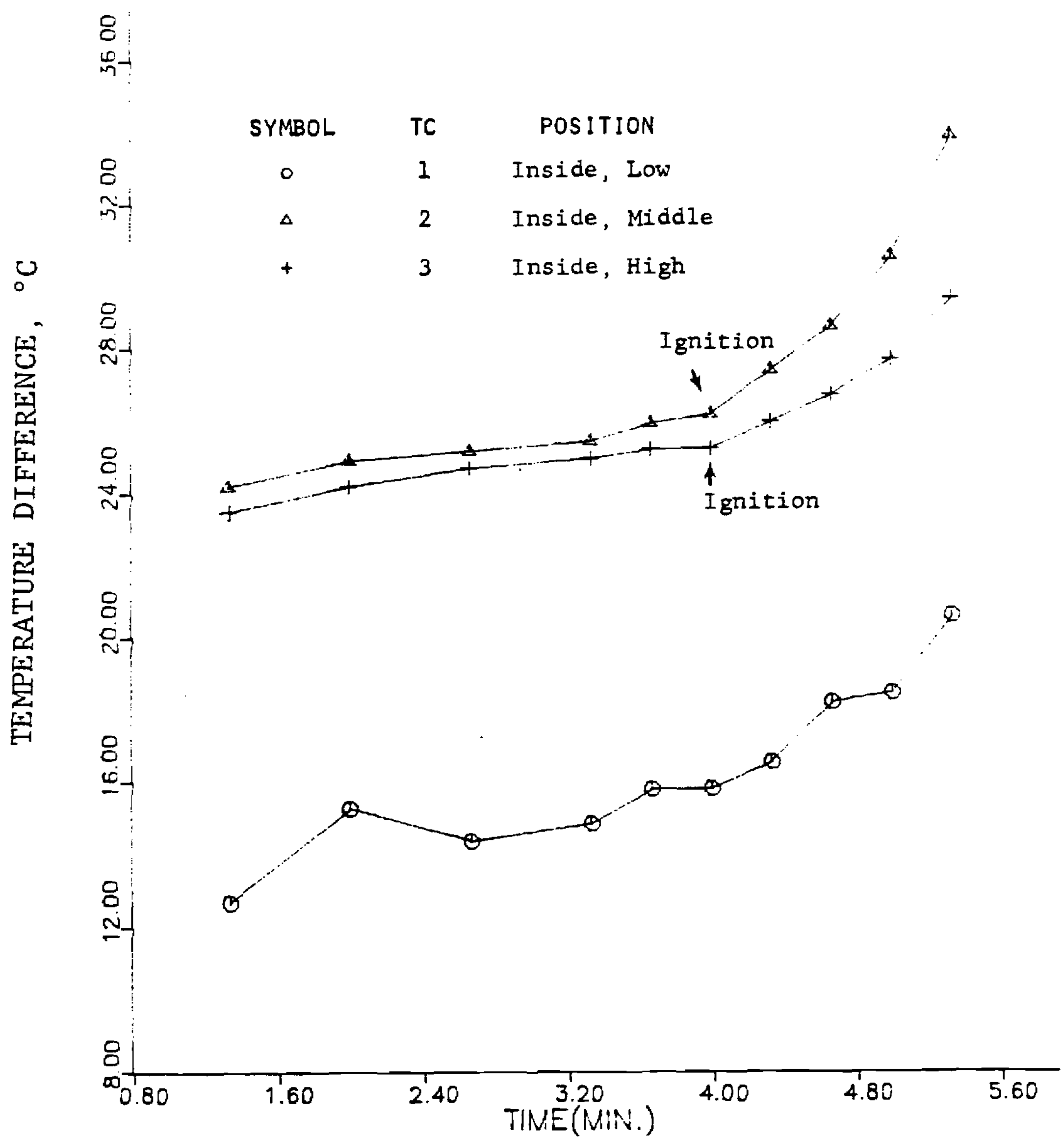


Figure 3.5. Typical Temperature Difference Curves for the Reaction Cell Thermocouples Showing the Onset of Pyrolyzate Ignition.

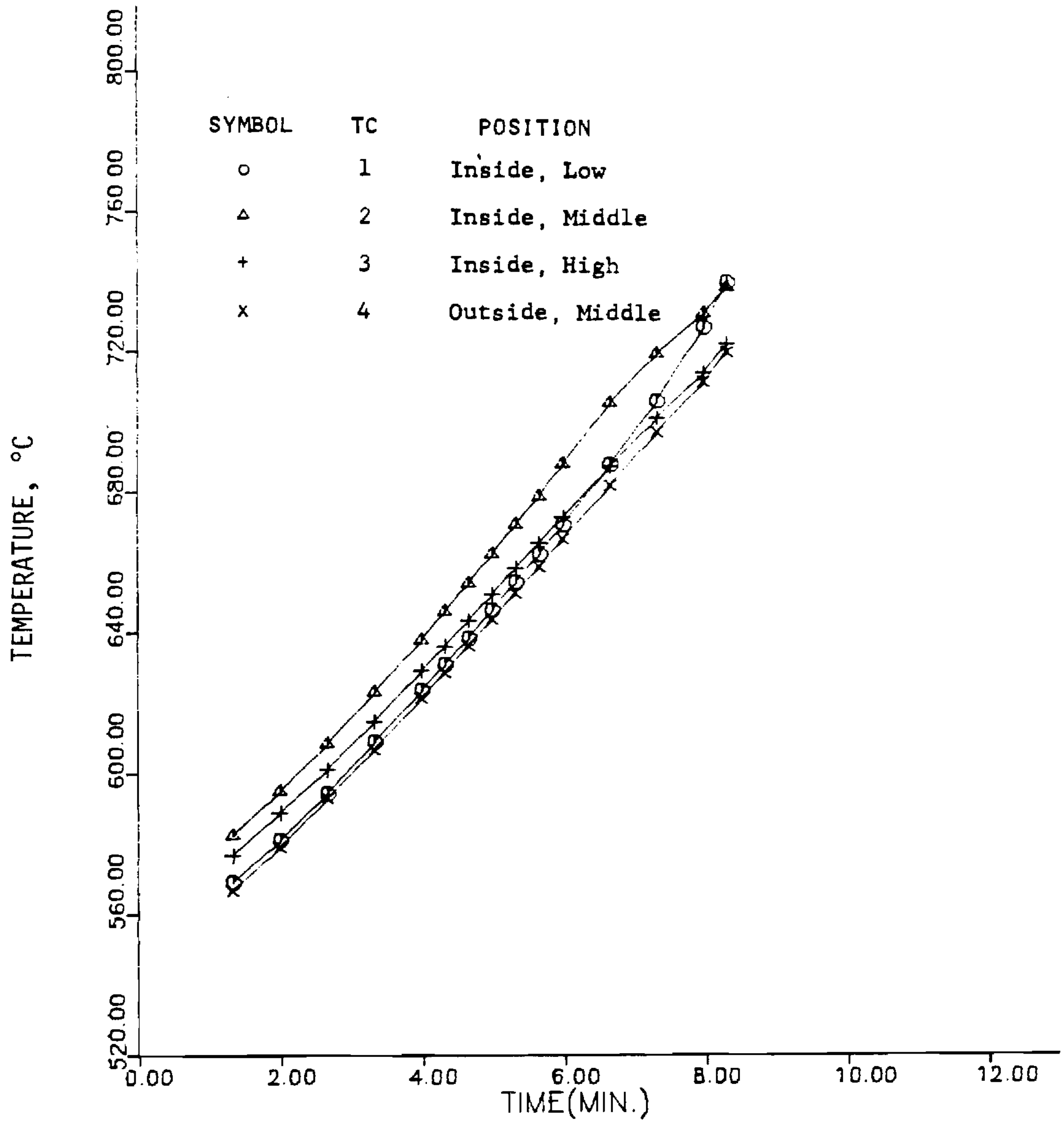


Figure 3.6. Typical Temperature Histories for the Reaction Cell Thermocouples, Showing the Onset of Pyrolyzate Ignition under Quenching Reaction Conditions.

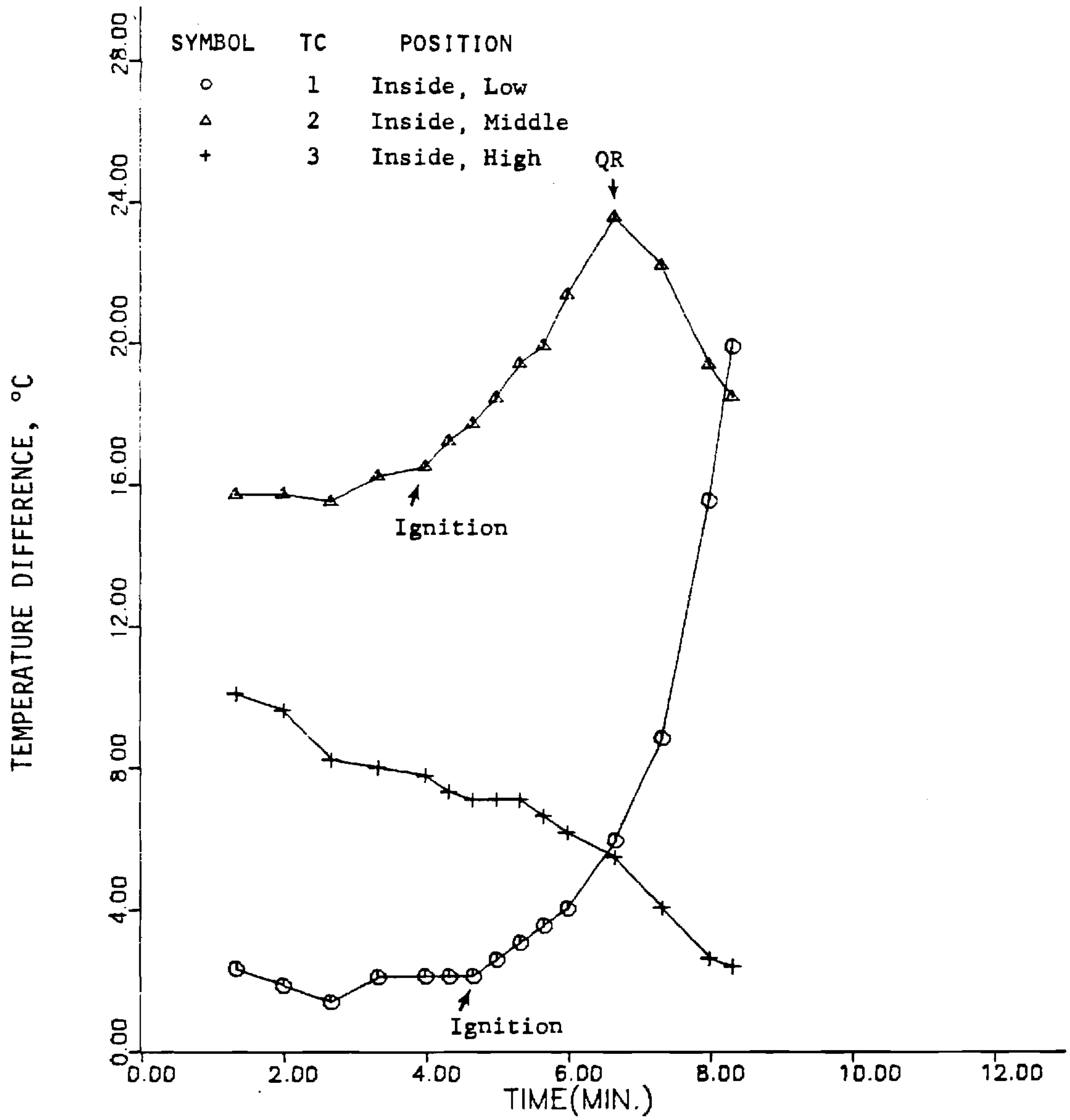


Figure 3.7. Typical Temperature Difference Curves for the Reaction Cell Thermocouples Showing the Onset of Pyrolyzate Ignition and the Quenching Reaction (QR).

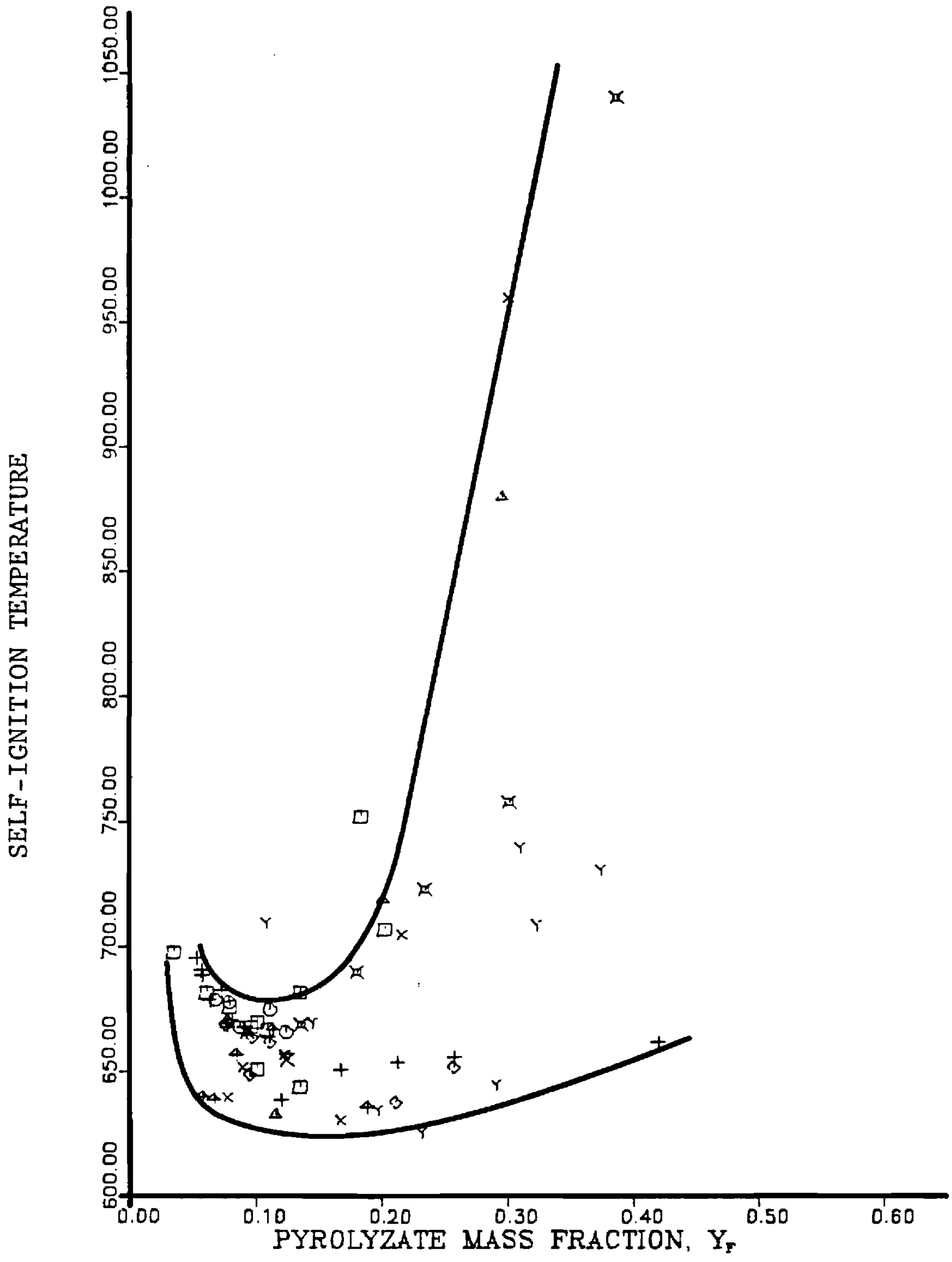


Figure 3.8. Minimum Self-Ignition Temperatures as a Function of Pyrolyzate Concentration for Bituminous Coal at Various Sizes, Initial Atmospheres and Heating Rates.

Key to Figure 3.8.

Symbol	Coal Particle Size µm	Initial Atmosphere	Heating Rate W/cm^2
□	149-247	N_2 trace	5
⦶	< 62	N_2 trace	5
+	< 62	N_2 trace	10
↑	< 62	18 cm Hg, N_2	10
⧗	< 62	28 cm Hg, N_2	10
⌧	< 62	73.7 cm Hg, N_2	10
×	< 62	N_2 trace	15
◇	< 62	Air Trace	10
Y	< 62	22.9 cm Hg, Air	10
△	< 62	45.7 cm Hg, Air	10

Using bituminous coal particles sized to pass through a 62 μm sieve, the effects of pyrolysis heating rate (Figure 3.9) and initial atmosphere (Figure 3.10) were studied. The higher heating intensity 15 W/cm^2 produced a narrowing of the ignition curve when compared to the 10 W/cm^2 intensity. Not enough data points were obtained to draw conclusions from the 5 W/cm^2 intensity.

The effect of increasing initial atmospheric pressure also narrows the pyrolyzate concentration range of ignitable mixtures. The ignition curves appeared indifferent as to whether air or nitrogen was used as an initial atmosphere.

Minimum self-ignition temperature measurements on pyrolyzate gases generated from lignite (brown) coal at two different intensities is shown in Figure 3.11. There appears to be no noticeable effect due to intensity for this sized coal and initial atmosphere conditions.

Comparison of minimum self-ignition temperature curves for bituminous and brown coals under similar pyrolysis conditions is made in Figure 3.12. The brown coal exhibits a broader and flatter ignition curve than the bituminous coal, if the quenching reaction points are excluded. Interestingly the difference in the ignition curves appears in the fuel rich limit. The ignition temperatures of the fuel lean region are comparable for both coals. The bituminous coal exhibits a slightly leaner limit than the brown, but the brown coal exhibits a greater rich limit. Table 3.1 lists ignition limits for the two coals and the various pyrolyzing conditions.

3.5.3. Molal Mass

For each pyrolysis run one or more gas samples were taken from the accumulator at 125-150°C to conduct an apparent molal mass measurement. These were averaged and the results are presented in Tables 3.2 and 3.3. The bituminous coal pyrolyzate apparent molal masses do not appear to be influenced by variations in incident heating rate for pyrolysis. However, the brown coal shows a significant apparent molal mass decrease as the incident heat flux was increased.

The effect of total pressure of the initial atmosphere is shown in Figure 3.13. The increase in apparent molal mass due to the addition of initial gas mass prior to pyrolysis is less than 15%. The trend of

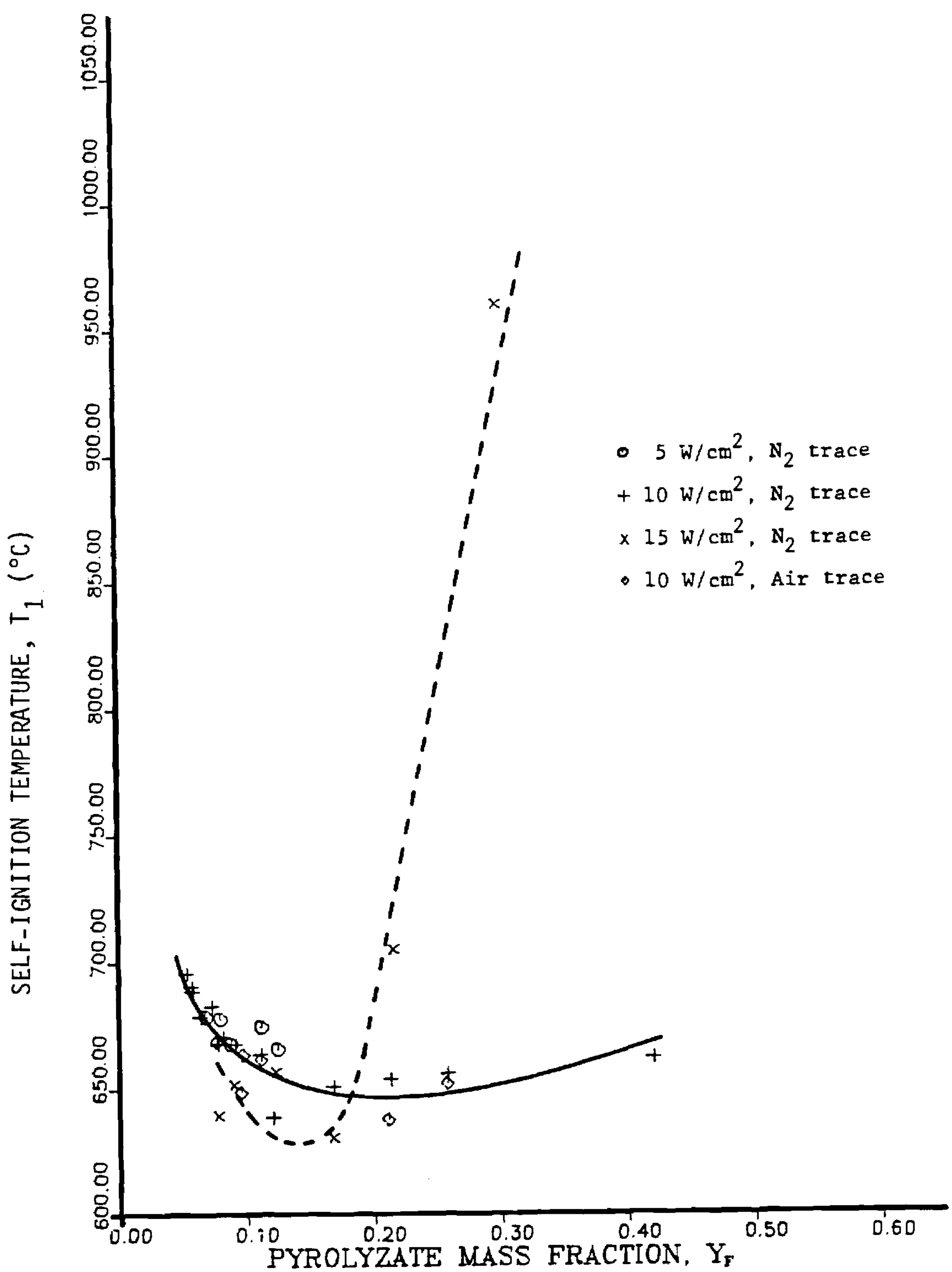


Figure 3.9. Minimum Self-Ignition Temperatures as a Function of Ignition Heating Rate for Pyrolysis, < 62 μm Particle Size Bituminous Coal.

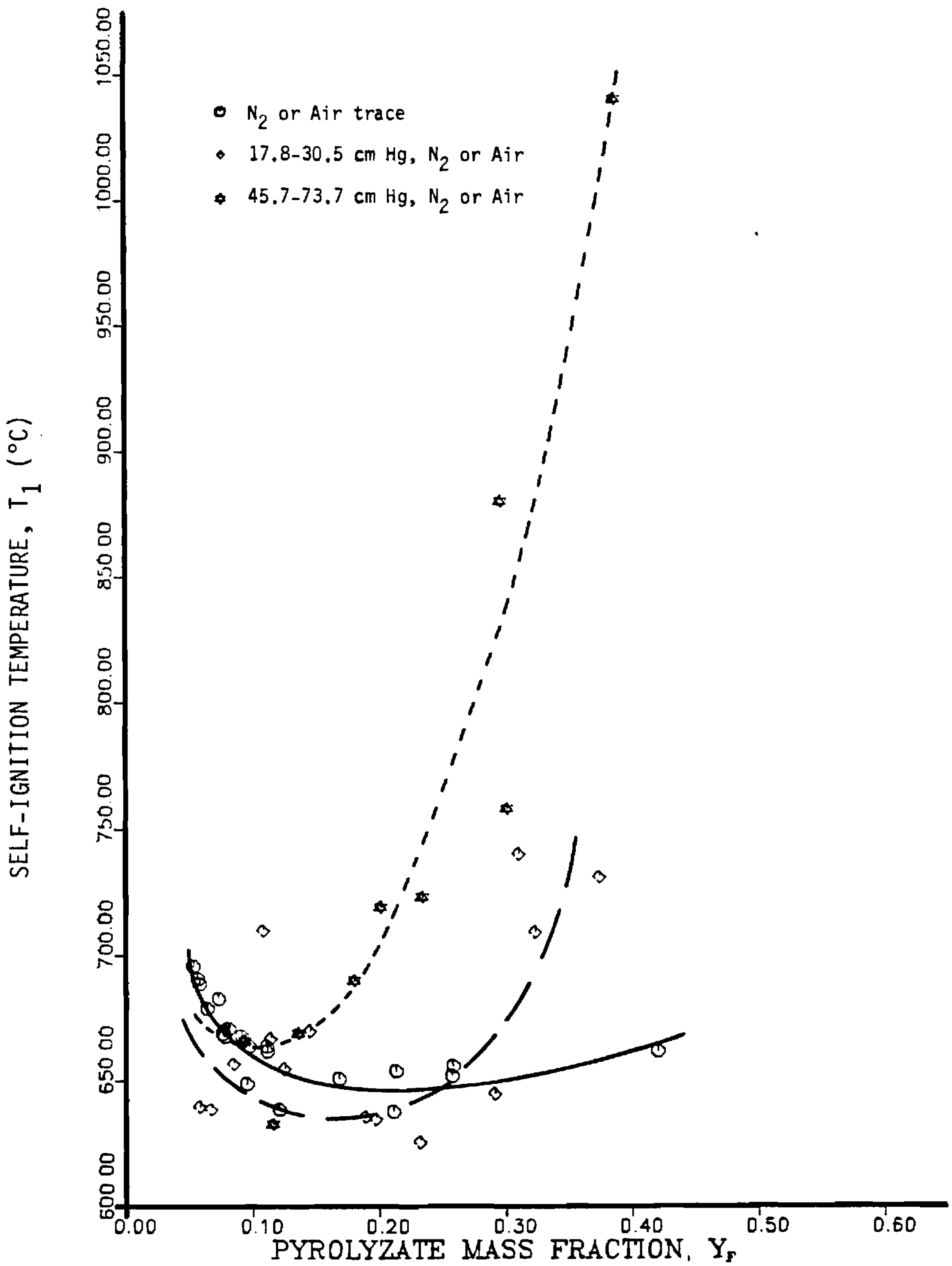


Figure 3.10. Minimum Self-Ignition Temperatures as a Function of Pyrolyzate Concentration for Bituminous Coal, < 62 μm, 10 W/cm^2.

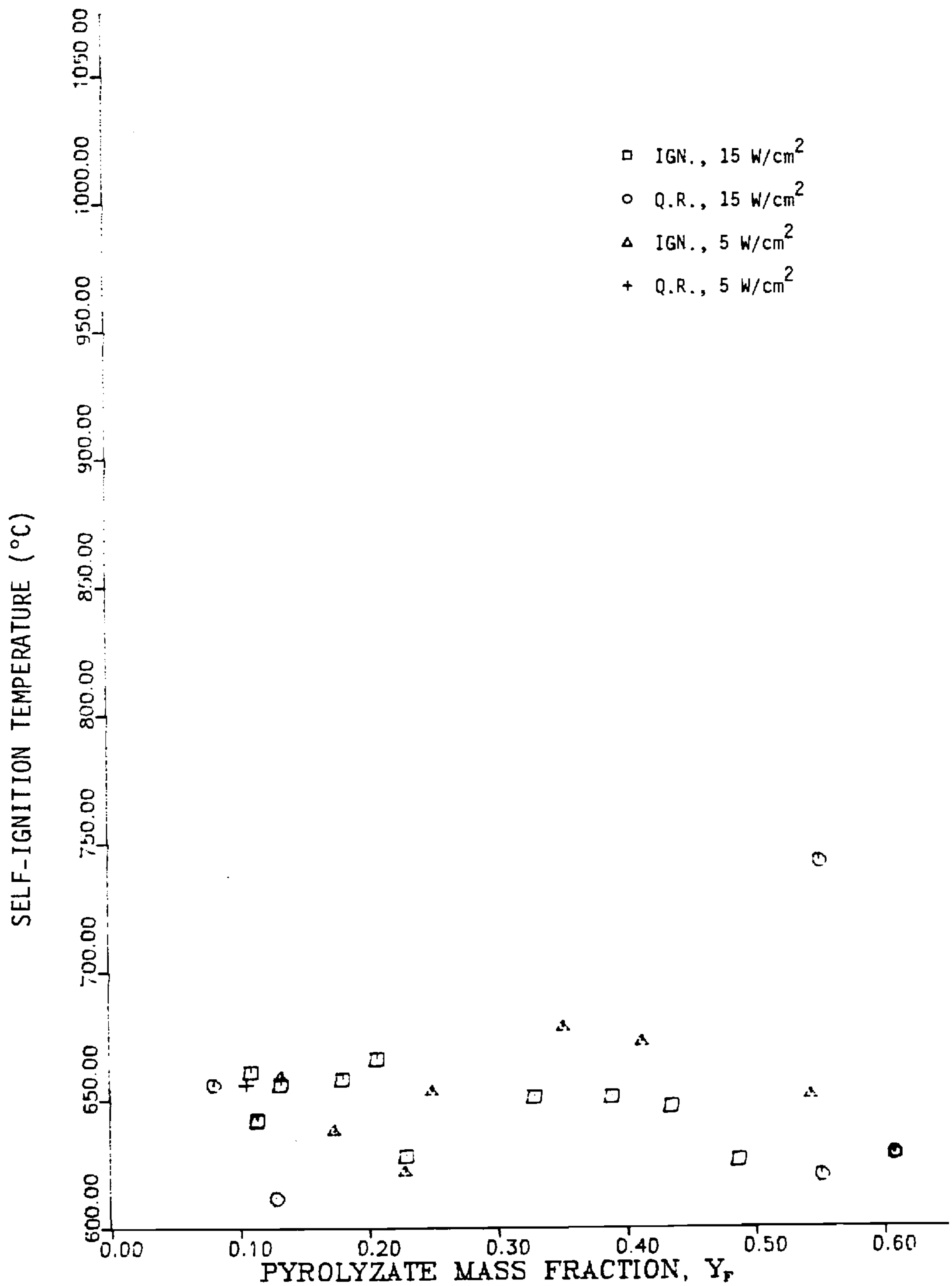


Figure 3.11. Minimum Self-Ignition Temperatures as a Function of Pyrolyzate Concentration for Brown Coal, < 53 μm, Pyrolyzed in Trace Air.

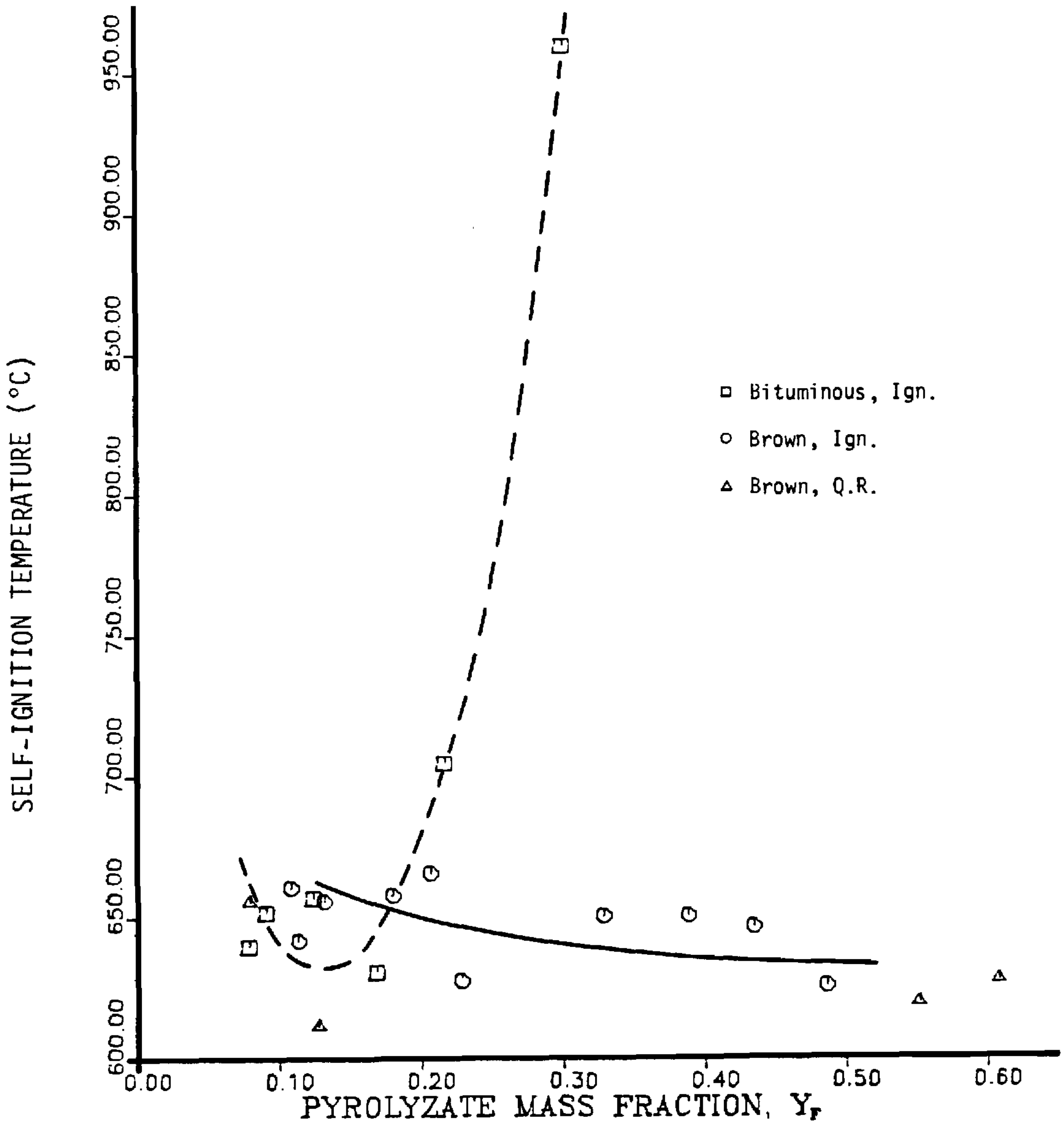


Figure 3.12. Minimum Self-Ignition Temperature as a Function of Pyrolyzate Concentration for Bituminous and Brown Coals, N_2 or Air Trace, < 53 μm, 15 W/cm^2.

Table 3.1. Ignition Limits for Pyrolyzate Gases of Bituminous and Brown Coal Particles Mixed with Air.

Coal	Coal Particle Size µm	Initial Atmosphere	Heating Rate W/cm^2	Pyrolyzate Concentration Limits: Range of Limits, Lean Y_F	Rich Y_F	Range Of Ignition Y_F
Bituminous	149-247	N_2 trace	5	0.019-0.036	0.203-0.230	0.036-0.203
Bituminous	< 62	N_2 or Air trace	10	0.040-0.054	0.421-0.647*	0.054-0.421
Bituminous	< 62	17.8-30.5 cm Hg, N_2 or Air	10	0.071	0.313-0.422	0.059-0.375
Bituminous	< 62	45.7-73.7 cm Hg, N_2 or Air	10	0.044-0.094	---	0.094-0.388
Brown	< 62	Air trace	5	0.106-0.133	---	0.133-0.544
Brown	< 62	Air trace	15	0.080-0.109	0.487-0.609*	0.109-0.487

*Including Quenching Reactions

Table 3.2. Apparent Molal Mass of Pyrolyzate Gases Generated from Bituminous Coal Particles

Coal Particle Size µm	Initial Atmosphere	Heating Rate W/cm^2	Number of Tests	Molal Mass g/g-mole	Standard Deviation
149-247	N_2 trace	5	7	21	2.1
< 62	N_2 trace	5	1	20	---
< 62	N_2 trace	10	2	17	0.4
< 62	28 cm Hg, N_2	10	1	18	---
< 62	73.7 cm Hg, N_2	10	2	25	0.4
< 62	N_2 trace	15	1	22	---
< 62	Air trace	10	2	18	1.6
< 62	22.9 cm Hg, Air	10	3	20	0.5
< 62	45.7 cm Hg, Air	10	1	23	---

Table 3.3. Apparent Molal Mass of Pyrolyzate Gases Generated from Brown Coal Particles

Coal Particle Size µm	Initial Atmosphere	Heating Rate W/cm^2	Number of Tests	Molal Mass g/g-mole	Standard Deviation
< 53	Air trace	5	2	29	0.1
< 53	Air trace	15	3	24	1.1

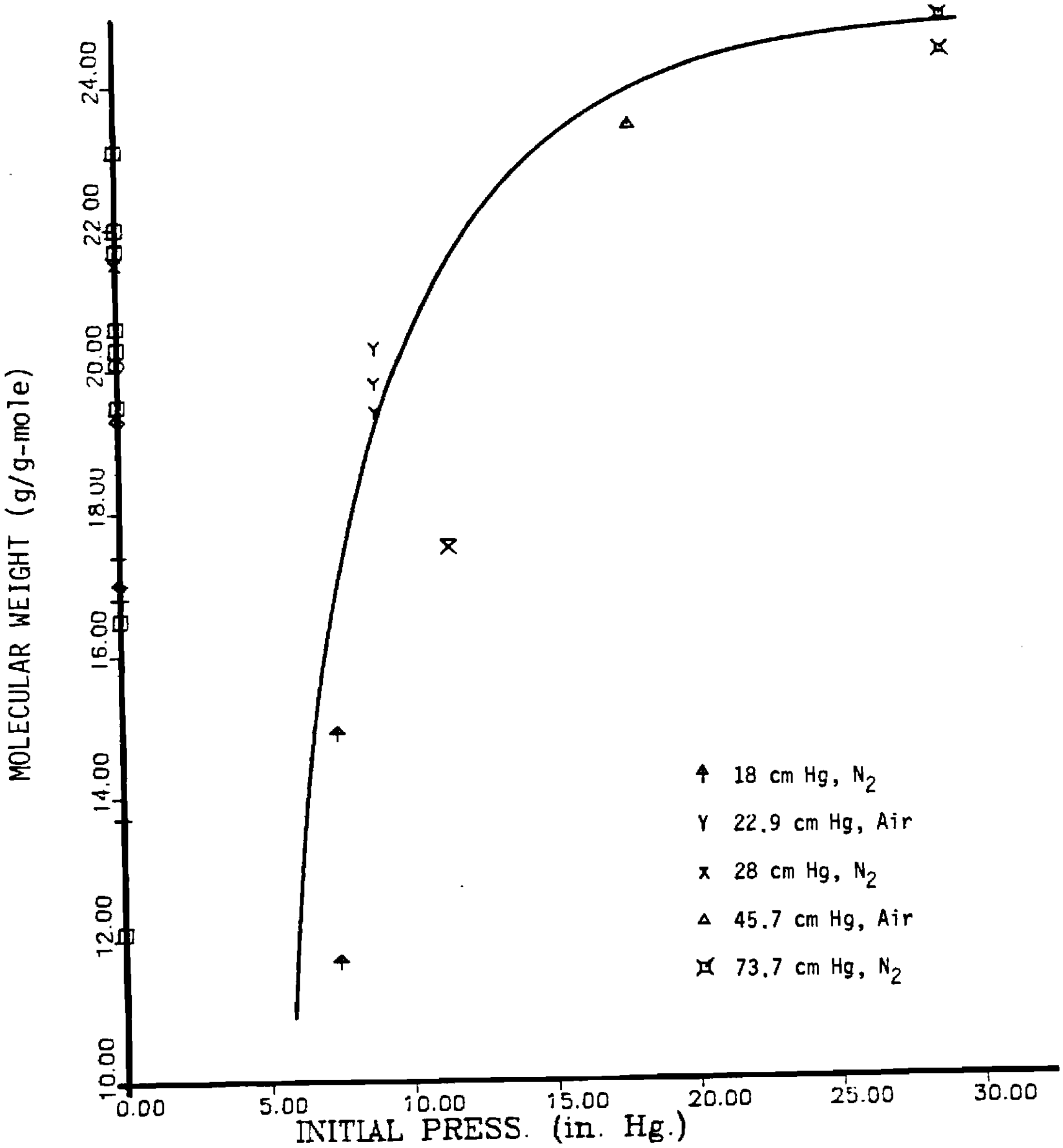


Figure 3.13. Apparent Molecular Weight as a Function of Initial Total Pressure Prior to Rapid Pyrolysis for Bituminous Coal, < 62 μm Particle Size, 10 W/cm^2 Pyrolysis Rate.

increasing molal mass with increasing initial atmosphere pressure exceeds this physical gas addition effect and must be attributed to the pyrolysis process itself.

3.5.4. Proximate Analysis

Proximate analysis on the two types of coals were carried out and these are reported in Section 2.5. In addition a proximate analysis was carried out on the solid residue left behind after the pyrolysis runs in LITACA. These results are summarized in Tables 3.4 and 3.5 for both unpyrolyzed and pyrolyzed coals. The analysis demonstrates that the majority of volatiles in the coals are driven off during the pyrolysis process. Remaining volatiles are suspected to be from tar condensation occurring during cooling down of LITACA subsequent to the pyrolysis run and ignition tests.

A comparison of proximate analyses for the virgin coal and the pyrolyzed coal residues was based on the assumption that the ash content remains unchanged. From this comparison the fixed carbon content is noted to decrease with bituminous coals but at a lessening degree as the initial atmosphere pressure is increased. The brown coals tested show a slight increase in fixed carbon with a higher value at the higher heating rate.

Phenomenologically the brown coals were noted to produce greater volumes of pyrolyzates per unit mass than the bituminous coals and in shorter periods of pyrolysis heating time. Additionally, the pyrolyzed bituminous coal residues tended to be tarry and filled with thin glassy carbon ribbons 5.0 mm or less in length. The brown coal residues contained no glassy carbon ribbons and tended to be less tarry.

3.6. Conclusions

Pyrolysis experiments have been carried out on two coals at heating rates near those experienced with regenerative pyrolysis, using the Lower Ignition Temperature and Concentration Apparatus. The resultants gases were characterized in terms of their minimum ignition temperatures

Table 3.4. Proximate Analysis Summary of Unpyrolyzed and Pyrolyzed Coals.

Coal Sample	Particle Size µm	Initial Atmosphere	Heating Rate W/cm^2	Number of Tests	Moisture %	Volatiles %	Carbon %	Ash %
Bituminous	< 53	---	---		3.0	32.1	52.4	13.5
Bituminous	< 53	N_2 trace	15	2	3.7	3.6	55.2	37.5
Bituminous	< 53	45.7 cm Hg, Air	10	2	3.5	7.5	60.1	28.9
Bituminous	< 53	73.7 cm Hg, N_2	10	2	2.9	6.2	70.8	20.1
Brown	< 53	---	---		11.1	35.8	42.6	10.1
Brown	< 53	Air trace	5	2	3.7	12.3	68.1	15.9
Brown	< 53	Air trace	15	2	7.7	7.7	69.7	7.7

Table 3.5. Changes in Proximate Analyses of Unpyrolyzed and Pyrolyzed Coals.

Coal Sample	Particle Size μm	Initial Atmosphere	Heating Rate W/cm^2	Fraction of Mass Remaining %	Fraction of Volatiles Remaining %	Change in Fixed Carbon %
Bituminous	< 62	N_2 trace	15	36.0	4.0	-62.1
Bituminous	< 62	45.7 cm Hg, Air	10	47.6	10.9	-46.4
Bituminous	< 62	73.7 cm Hg, N_2	10	67.2	13.0	-9.3
Brown	< 62	Air trace	5	63.5	21.8	+1.5
Brown	< 62	Air trace	15	67.8	14.6	+10.9

and apparent molal mass. The ignition temperatures on the fuel lean regions do not appear to be greatly effected in terms of the variables considered in this investigation. On the other hand, the fuel rich limit ignition temperatures have shown a dependence on the magnitude of the initial atmosphere used. Some differences have also been found both in the flammability limits and in the ignition temperature curves, in comparing pyrolyzates generated from bituminous and brown coals. These studies clearly demonstrate the need for further studies using higher heating rates, chemical analysis and control of both the heating rates and the maximum temperature during pyrolysis.

4. COMBUSTION OF COAL AND CHAR

4.1. Purpose

The purpose of the coal and char combustion task is to study the effect of regenerative pyrolysis on the particles. The flat flame burner with the opposed gas-particle jet will be used for these studies. Variables to be considered are the type of fuel, particle size, level of preheating, composition of the carrier gas and composition of the oxidizing atmosphere.

4.2. Achievements

The two coals used in the ignition and pyrolysis studies were also used in the present studies. Temperature profiles using a Y-construction thermocouple, were recorded in the flat-flame burner reaction zone. A computer program was developed to translate the temperature profiles into isotherms and graphically display these isotherms. Photographs were made of the particle tracks in the reaction zone and particle speeds were determined from these photographs.

Using a micropyrometer coal particle and char particle temperatures were measured in the flat-flame burner reaction zone. Finally the gas-particle flow rates were raised, the fuel of the flat-flame burner was turned off and the condition of self-sustained combustion of the coal particles were determined.

4.3. Apparatus and Instrumentation

The flat-flame burner with the opposed gas-particle nozzle used in the ignition studies discussed in Chapter 2 was also used for the combustion studies. Detailed description of the flat-flame burner, the particle feed system and the temperature measuring instrumentation are presented in Appendix A.

4.4. Experimental Procedure

The experimental procedure described in Section 2.4 was also followed for the combustion studies measurements concerning temperature profiles in the gas flow. These were corrected in the manner described in the same section.

Temperature measurements of the particles were carried out using the micropyrometer as soon as all the desired variables were established under steady-state conditions. The micropyrometer was then focused on the particles and the filament current adjusted to achieve equal intensity. These particle measurements were carried out below the nozzle and adjacent to the nozzle.

Establishment of the self-sustaining condition was investigated by setting up the burner and gas-particle flow at the same level. The burner fuel was then turned off and the flat flame was allowed to extinguish. If the system will maintain self-sustaining combustion for at least a period of a few minutes the conditions were recorded. The burner was then turned on again and the same process repeated with either lower or high gas-particle flow. Thus for each fuel and for each gas-particle nozzle the lower limit was established.

4.5. Results

The results of fuel and burner characterization have been presented in Sections 2.5.1 and 2.5.2 respectively. Similarly the gas temperature profiles and the resultant isotherms were included in Section 2.5.3 and Appendix B. As indicated from these figures, there is a distinct behavior between the lignite and bituminous coal particles and this is manifested in differences in the gas temperatures shown in Figures 2.12-2.14.

Coal particle temperature resulting from the micropyrometer use are shown in Tables 4.1 and 4.2 for two different groups of particles and for the two fuels used. These particles are well in excess of the gas temperatures presented as isotherms in Section 2.5.3 for the region under the nozzle. The temperatures adjacent to the nozzle, on the other hand, are very nearly equal for the particles and the gas.

Table 4.1. Coal Particle Temperatures, < 53 μm Particles

Equivalence Ratio ϕ	Carrier Gas	Bituminous Under Nozzle °C	Bituminous Adjacent to Nozzle °C	Lignite Under Nozzle °C	Lignite Adjacent to Nozzle °C
0.67	AIR	~1100	~910	1050-1100	910-930
	N_2	1000-1010	860-880	910-940	850-860
0.86	AIR	1060-1070	940-950	1060-1070	910-930
	N_2	1000-1010	910-920	900-930	860-890

Table 4.2. Coal Particle Temperatures, 53-74 μm, Particles

Equivalence Ratio ϕ	Carrier Gas	Bituminous Under Nozzle °C	Bituminous Adjacent to Nozzle °C	Lignite Under Nozzle °C	Lignite Adjacent to Nozzle °C
0.67	AIR	1070-1080	910-920	1070-1090	910-930
	N_2	1000-1010	840-850	940-960	850-870
0.86	AIR	1120-1130	860-880	1060-1070	880-900
	N_2	960-980	920-940	810-830	770-800

Visual observations with both bituminous and lignite coal particles have also shown some distinct behavior in the combustion of the coal and char. In the case of lignite coal, deposits on the outside wall of the nozzle were found to be primarily ash. In contrast, coupled with the expulsion of volatiles for the bituminous coal particles, black smoke (soot) was observed flowing upwards outside the gas-particle nozzle and deposit of soot particles were found on the outside surface of the tube and inside surface of the pyrex chimney.

Photography carried out with the particle combustion was used to observe both ignition and behavior of particles in the reaction zone of the flat-flame burner. These photographs have also served to evaluate particle speeds adjacent to the gas-particle nozzle and they range from 89 cm/s to 157 cm/s.

Self-sustaining combustion conditions have been determined and these are shown in Table 4.3. The distinct difference between the two types of fuels is that it is possible to sustain the combustion of lignite at a lower rate in the absence of the flat flame above the burner matrix.

Table 4.3. Conditions for Self-Sustaining Combustion

Nozzle Size o.d. cm	Nozzle Height H cm	Fuel Type (53-74 μm)	Burner Air Rate $\dot{m}_a$ g/h	Carrier Gas (Air) Rate $\dot{m}_{cg}$ g/h	Particle Flow Rate $\dot{m}_c$ g/h
2.54	2.0	Bituminous	2350	142.9	~0.9
	2.0	Brown	2350	124.1	~0.75
	2.0	Brown	2350	85.9	~0.46
1.27	2.0	Bituminous	2350	85.0	~0.47
	2.0	Brown	2350	85.0	~0.46
	2.0	Brown	2350	41.1	~0.11

4.6. Conclusions

Preliminary measurements carried out with the flat-flame burner with the opposed gas-particle jet have been successful in determining some quantitative and qualitative behavior for two types of coal particles. Sooting was found to accompany the combustion of bituminous coal particles and not of the lignite particles. Gas and particle temperatures were found to be different for the two types of coal particles. The flow rates of carrier gas and particles required to self-sustain combustion of bituminous coal particles was found to be higher than those required for lignite coal particles. These preliminary studies show the need for more detailed measurements of gas composition and erosion rate of particles in the reaction zone to evaluate further the effects of regenerative pyrolysis.

5. PRELIMINARY MODELING ANALYSIS

5.1. Introduction

It is of interest to couple the experimental program of the regenerative pyrolysis of coal particles with mathematical modeling of the various processes encountered. However, preliminary studies shall concentrate on the mathematical description of the processes within the carrier-gas-particle injector nozzle.

The objective of the present analysis, then, is to predict: (i) velocity, temperature and concentration profiles throughout the particle injector nozzle, and (ii) heating conditions that will lead to pyrolysis and ignition of the coal particles within the nozzle.

5.2. Problem Formulation

The model assumes steady state conditions of a solid-gas mixture flowing through a heated, constant area duct (see Figure 5.1). The particle injector nozzle wall is assumed to have a known temperature distribution that varies along its length. This temperature profile may be specified from experimental measurements discussed in earlier sections of this report. Throughout the nozzle the coal particles and carrier gas are assumed in local thermodynamic equilibrium. At the nozzle entrance the particle density, carrier gas composition and solid-gas mixture flow rate and temperature are assumed known. Pressure effects are neglected and thermophysical properties and reaction kinetics parameters are assumed to be constant.

5.3. Model Simplifications and Parameter Ranges

The variables affecting the pyrolysis and ignition of the coal particles are: (i) heating rate of the solid-gas mixture, (ii) the mixture flow rate, (iii) the nozzle dimensions, (iv) the particle density, and (v) the initial carrier gas composition. The intimate interactions of these variables makes evident the complexity of the

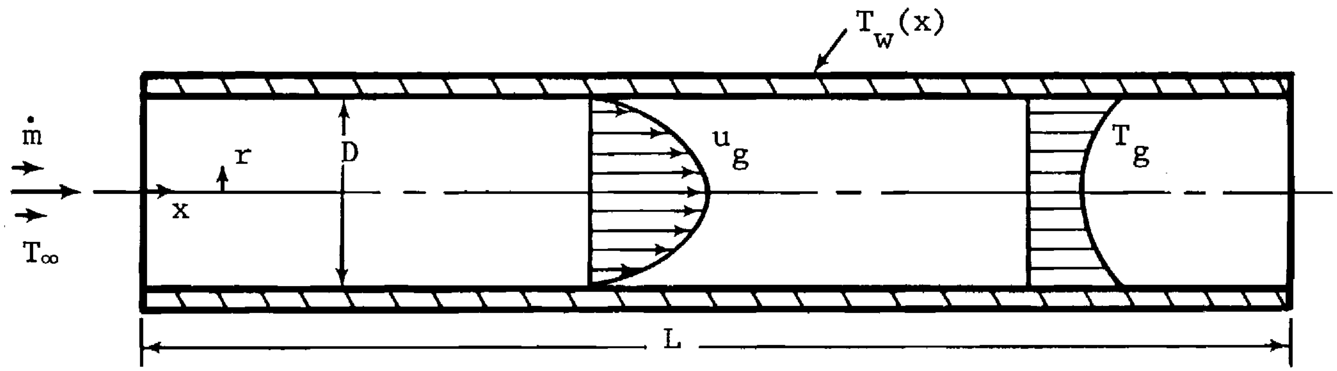


Figure 5.1. Coordinate System of the Gas-Particle Flow System Heated through the Wall.

analysis.

To develop a preliminary understanding of these variables and their influence on regenerative pyrolysis and coal particle ignition, further simplifications are made. In addition, the experimental flow rates, temperatures and nozzle dimensions of Task I are used to determine rough estimates of the variable ranges.

Calculations are based on the carrier gas flow rates and neglecting particle effects. For the range of carrier gas mass flow rates and the range of nozzle diameters selected, the Reynolds numbers are well within the laminar flow regime for duct flow. Assuming steady, incompressible laminar flow within a constant area duct and with constant properties, the centerline velocity may be calculated [38]. From the nozzle length and centerline velocity, the centerline residence time for a fluid element may be determined. If this fluid element enters the nozzle at the ambient temperature and exits the nozzle heated to some elevated temperature (300 K and 800 K, respectively), a heating rate is obtained using the residence time. Table 5.1 lists estimated values for these parameters. Note that the carrier gas is assumed to be air and that its density and dynamic viscosity have been evaluated at one atmosphere and an effective nozzle temperature of 600 K.

Table 5.1. Estimated Values of Parameters for the Heated Gas-Particle Flow in a Duct

Nozzle Diameter d cm	Carrier Gas Flow Rate $\dot{m}_{cg}$ g/hr	Reynolds Number Re_d	Centerline Velocity u_o cm/s	Centerline Residence Time τ_o s	Heating Rate °C/min	Feeder Type
0.635	10	9.23	21.3	1.34	2.239×10^4	Aspirator
	100	92.3	213.0	0.13	2.239×10^5	
	70	137.6	149.1	0.19	1.579×10^5	Screw
	180	353.6	383.3	0.074	4.054×10^5	
2.54	10	36.9	1.33	21.4	1.402×10^3	Aspirator
	100	369.0	13.3	2.14	1.402×10^4	
	70	34.4	9.32	3.06	9.804×10^3	Screw
	180	88.6	24.0	1.19	2.521×10^4	

6. PUBLICATIONS AND PRESENTATIONS

The research results, of the present grant period on the combustion of coal in an opposed gas-particle jet with regenerative pyrolysis, have been presented as follows:

(i) Durbetaki, P., "Combustion of Coal in an Opposed Gas-Particle Jet with Regenerative Pyrolysis," Combustion Phenomena Contractors Review Meeting, United States Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, 19 September 1979.

(ii) Wolfe, V. L., Jr., McAuliffe, G. H., and Durbetaki, P., "Preliminary Studies in Rapid Pyrolysis of Coal," 1979 Technical Meeting, The Eastern Section, The Combustion Institute, Georgia Institute of Technology, Atlanta, GA, 7-9 November 1979.

(iii) Durbetaki, P., Wolfe, V. L., Arthur, W. R., McAuliffe, G. H. and Gibbs, R. T., "Preliminary Studies in the Pyrolysis of Coal and Wood," Western States Section, The Combustion Institute, Irvine, CA, 21-22 April 1980, Paper No. WSS 80-23.

(iv) Nguyen, L., Wolfe, V. L., and Durbetaki, P., "Coal Combustion Studies with Regenerative Pyrolysis," Fall Technical Meeting, Eastern States Section, The Combustion Institute, Princeton, New Jersey, 12-14 November 1980.

An extended abstract of presentations (ii) and (iv) above were published in the book of abstracts.

APPENDICES

APPENDIX A

FLAT FLAME BURNER AND ASSOCIATED INSTRUMENTATION

A.1. Flat Flame Burner

The flat flame burner with the opposed gas-particle jet has been designed, built and modified to meet the following specifications:

(a) Establish a flat flame under steady-state conditions,

(b) Provide a gas or a combined gas-particle jet along the same axis and in opposed flow to the combustible mixture, and

(c) Afford temperature and gas composition measurements radially and axially.

The six major components of the apparatus are:

(i) Mixing chamber,

(ii) Burner tube and porous burner disc,

(iii) Glass chimney,

(iv) Stainless steel injection nozzle,

(v) Flow control and metering system, and

(vi) Particle feed system.

The flat flame burner as shown in Figure A.1, has methane and air entering at the bottom of the mixing chamber. The chamber is made of a steel pipe which is 61 cm long and has a 25.4 cm i.d. Inside the upper section of the chamber are located six 200 mesh stainless steel screens which are placed 3.8 cm apart from each other. A cast aluminum transition piece connects the mixing chamber to the brass burner tube. The burner tube is 36.8 cm long and has an 8.33 cm i.d. Close to the bottom of this tube is a 30 mesh stainless steel screen. From this point the tube is filled with 3 mm diameter glass beads up to 8 cm from the top of the burner tube. These beads are used for a final gas mixing and also to obtain an even flow of the gas mixture.

At the top of the burner tube, a sintered bronze porous disc is held in place by a bronze ring and three set-screws. This disc is used

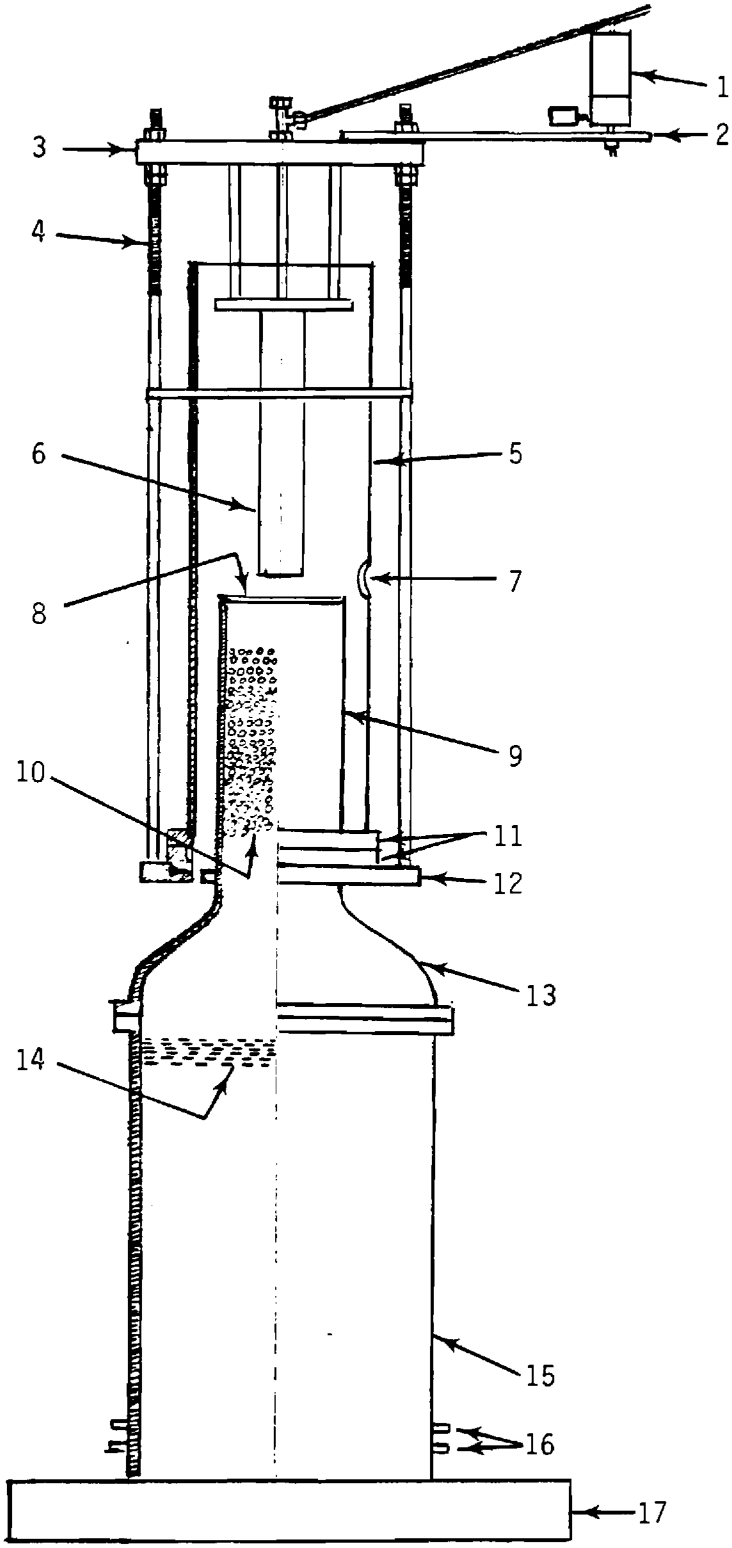


Figure A.1. Schematic of the Flat Flame Burner System.

Key to Figure A.1

1. Particle Feed Unit
2. Aluminum Plate
3. Injection Nozzle Steel Support Ring
4. Supporting Rods
5. Pyrex Glass Chimney
6. Injection Nozzle
7. Open Window
8. Porous Bronze Burner Disc
9. Brass Burner Tube
10. Glass Beads
11. Removable Aluminum Support Ring
12. Fixed Aluminum Support Ring
13. Cast Aluminum Transition Piece
14. 200 Mesh Stainless Steel Screens
15. Steel Tube Mixing Chamber
16. Methane and Air Inlets
17. Steel Support Carriage

as a flame holder and at the same time it prevents flash-back.

The opposed gas-particle jet assembly is located above the burner. The flow enters through a 6.4 mm diameter inlet tube which connects with a stainless steel injection nozzle. Two different nozzle sizes were used, one with a 1.27 cm o.d. and one with a 2.54 cm o.d. Both nozzles are 30.5 cm long. The nozzle is supported by a steel plate which in turn is connected to a steel support ring attached around the top of the cast aluminum transition piece. Thus, the jet assembly design makes it possible for the injection nozzle exit to be located at different heights above the top of the burner sintered bronze disc.

A pyrex glass chimney encloses the injection nozzle and burner tube. This chimney is 61 cm long and has a 15.2 cm i.d. The chimney is supported by aluminum support rings of various heights. A 5.0 cm diameter port hole in the chimney provides access to the hot gas region of the burner for temperature and species sampling of the flame. An asbestos fiber material was used to cover the port hole and at the same time allow the traversing of the probe by means of a small slit cut in the material.

A.2. Gas Flow System

The gas flow system for the combustibles through the burner and the carrier gases through the particle feed systems were arranged in two different configurations. One arrangement was used in association with the fluidized-bed-aspirator particle feed system. The flow diagram for this arrangement is shown in Figure A.2. The second arrangement was used in association with the simple fluidized bed particle feed system. The flow diagram for this second arrangement is shown in Figure A.3.

A.3. Particle Feed Systems

Three particle feed systems were designed, built and introduced at different stages of the research activity. Only one of the three powder feed systems was used during any given test. The first of these three systems was a Metco Powder Feed Unit. This unit was modified and adapted with a screw type particle feed system. Details

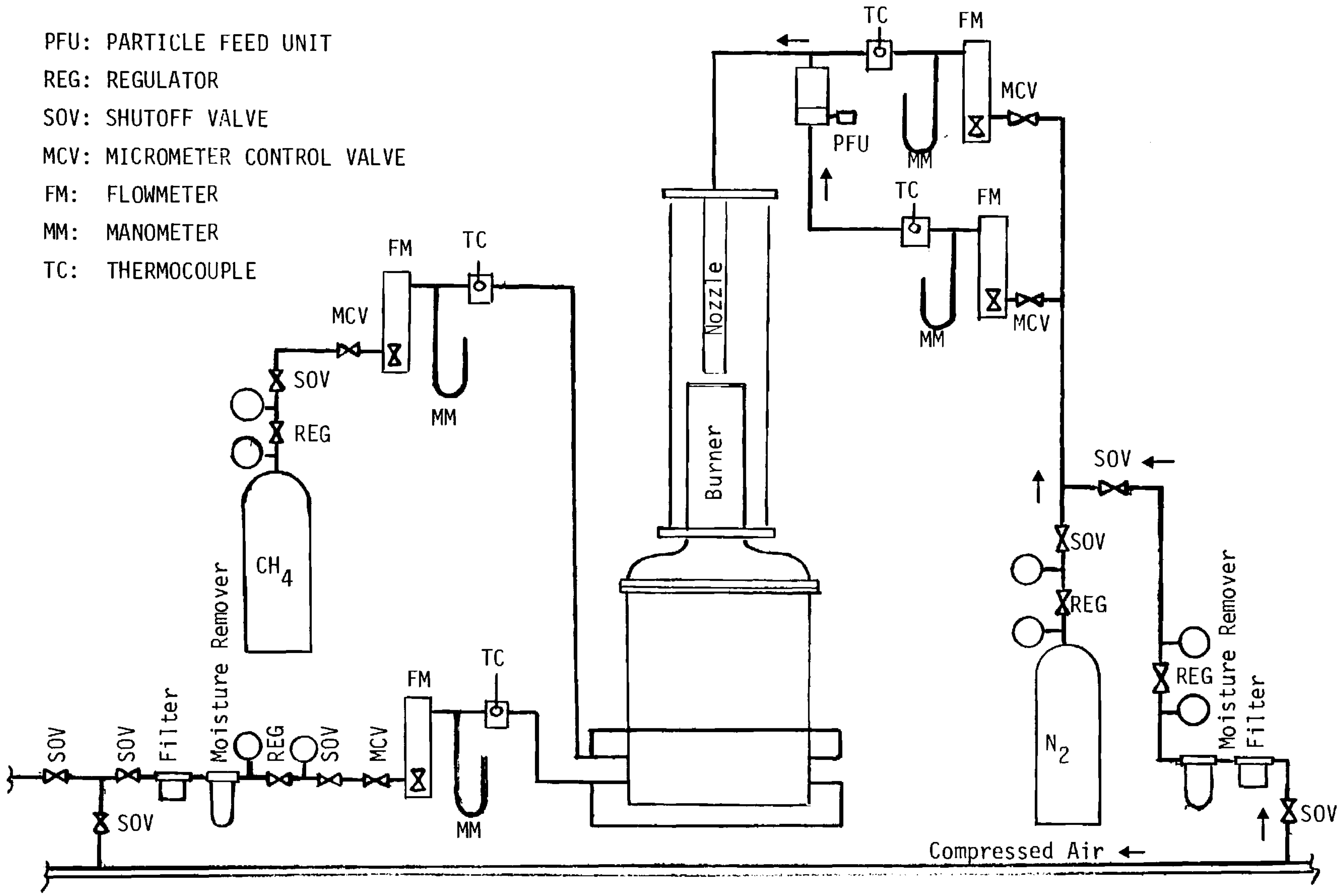


Figure A.2. Schematic of the Flat Flame Burner Coupled with the Fluidized-Bed-Aspirator Particle Feeder with Fuel, Air and Carrier Gas Flow Paths.

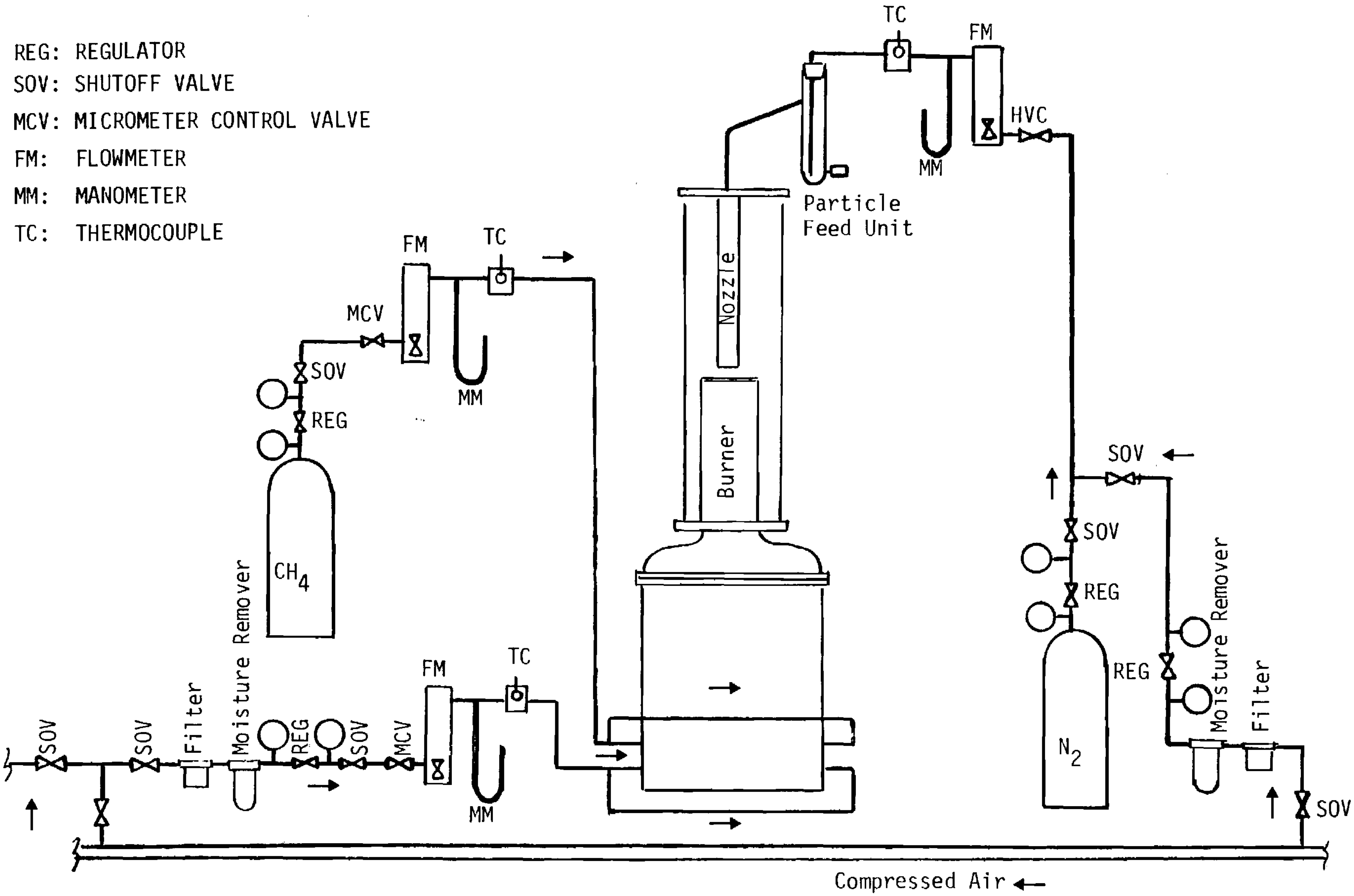


Figure A.3. Schematic of the Flat Flame Burner Coupled with the Simple Fluidized Bed Particle Feeder with Fuel, Air and Carrier Gas Flow Rates.

of the screw are shown in Figure A.4. A small D.C. motor was used to drive the screw, powered by a D.C. power supply, Hewlett Packard Model 6205B. A magnetic pickup gear was mounted on the shaft coupling the powder feed screw to the motor and together with an Electro Products Model 3045A magnetic pickup and a Hewlett Packard Model 5233L electronic counter it provided a means of determining the speed of rotation of the powder feed screw.

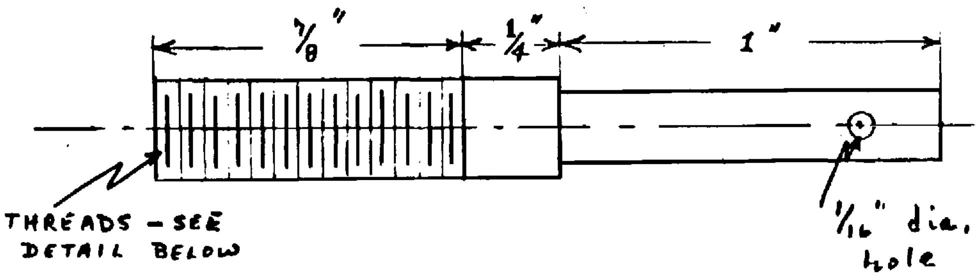
The second powder feed unit coupled a fluidized bed system with an aspirator. A schematic of the powder feed unit is shown in Figure A.5. As shown in the diagram the carrier gas was used to fluidize the coal particles resting on top of a stainless steel screen. A second stream of the carrier gas was used in the venting tube as the aspirator fluid and the entire system was coupled to the gas-particle injection nozzle of the flat flame burner as shown in Figure A.2.

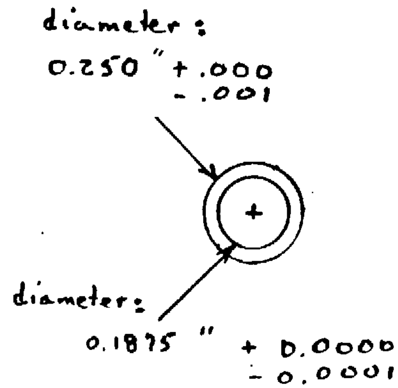
The third powder feed unit consisted of a 6 mm diameter inlet tube passing through a rubber stopper in the top of a test tube with the end of the inlet tube approximately 1-2 cm above the bottom of the test tube. A 6 mm diameter gas-particle exit tube provided the path between the particle feed system and the gas-particle injection nozzle of the flat flame burner. A schematic view of this fluidized bed particle feed system is shown in Figure A.6. The gas flow diagram incorporating this system is shown in Figure A.3.

A.4. Temperature Measuring Systems

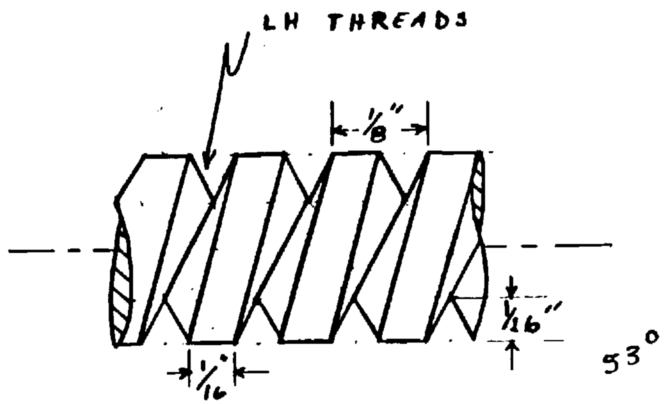
Temperature measurements were divided into two groups: those concerned with the gas flow measuring variable area flow meters and those concerned with temperatures in the reactive flow field. The temperature measurements in the gases flowing through each of the flow meters was carried out using iron-constantan thermocouples, placed downstream from the meter, referenced to 0°C through use of an Omega Ice-Point Cell and their output displayed on a digital millivoltmeter, Hewlett Packard Model 3465A.

The gas temperatures in the reaction zones, both above the burner matrix and inside the gas-particle nozzle were measured by chromel-alumel thermocouples. These thermocouples were also referenced to 0°C

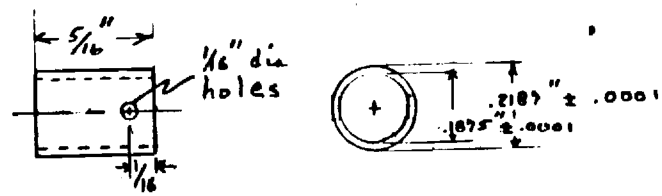




Drawing No. 1-A
Particle Feed Screw
Scale: 2:1



Drawing No. 1-B
Screw Thread Detail
Scale: 4:1
Material: Brass



Drawing No. 2
Screw Sleeve
Scale: 2:1
Material: Aluminum

Figure A.4. Details of Screw for Particle Feed System.

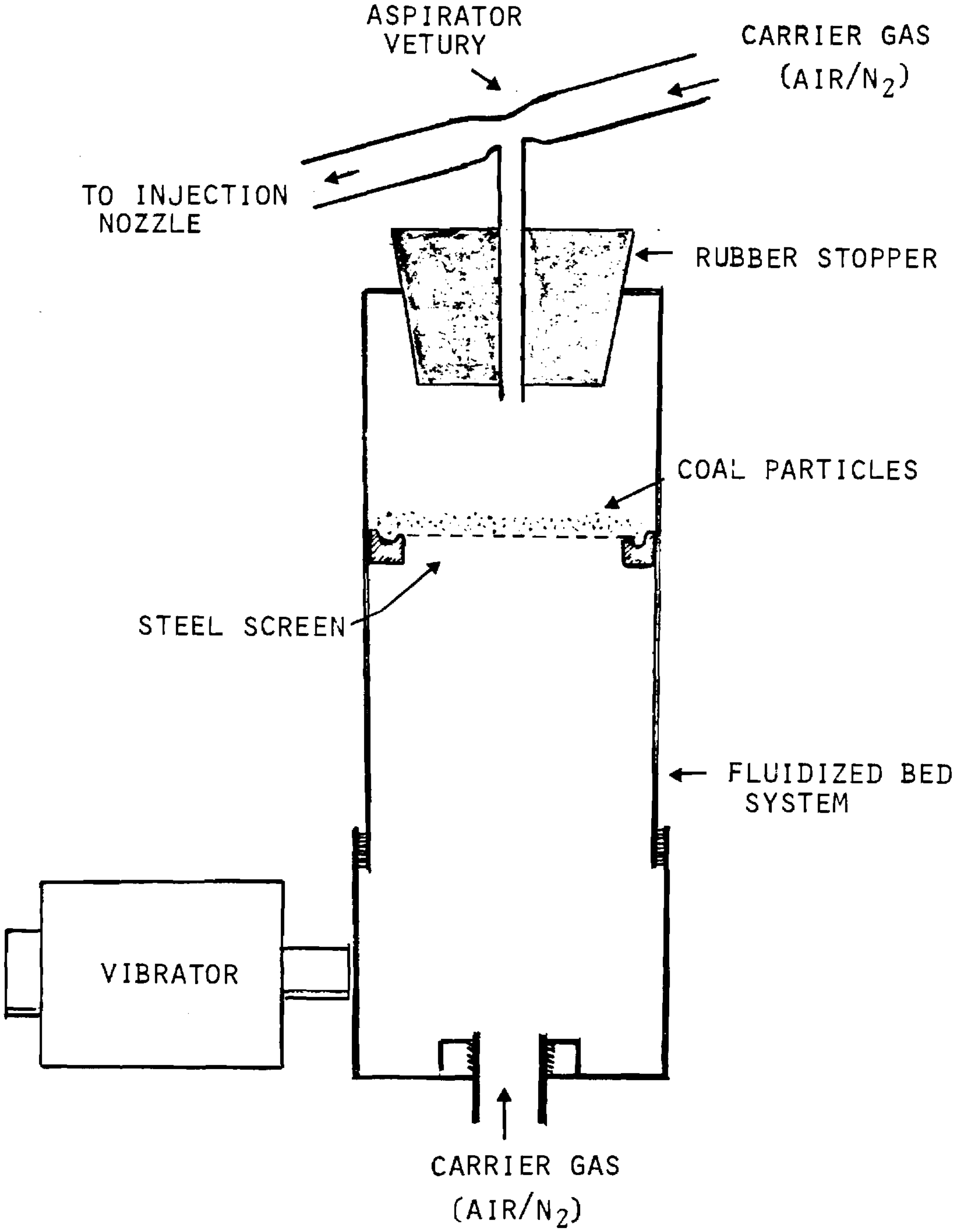


Figure A.5. Schematic of Powder Feed Unit Coupling a Fluidized Bed System with an Aspirator.

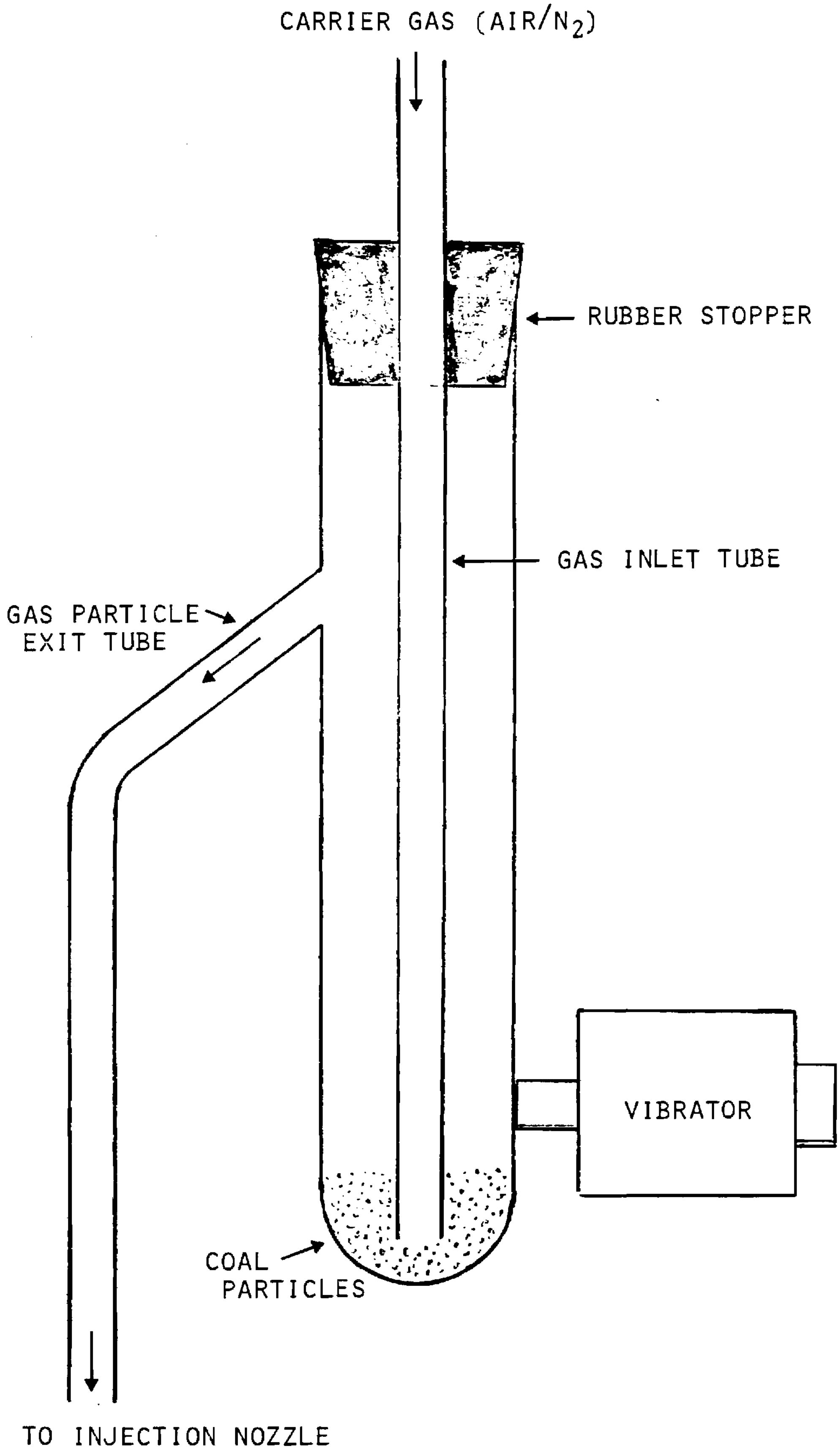


Figure A.6. Schematic of the Simple Fluidized Bed Particle Feed System.

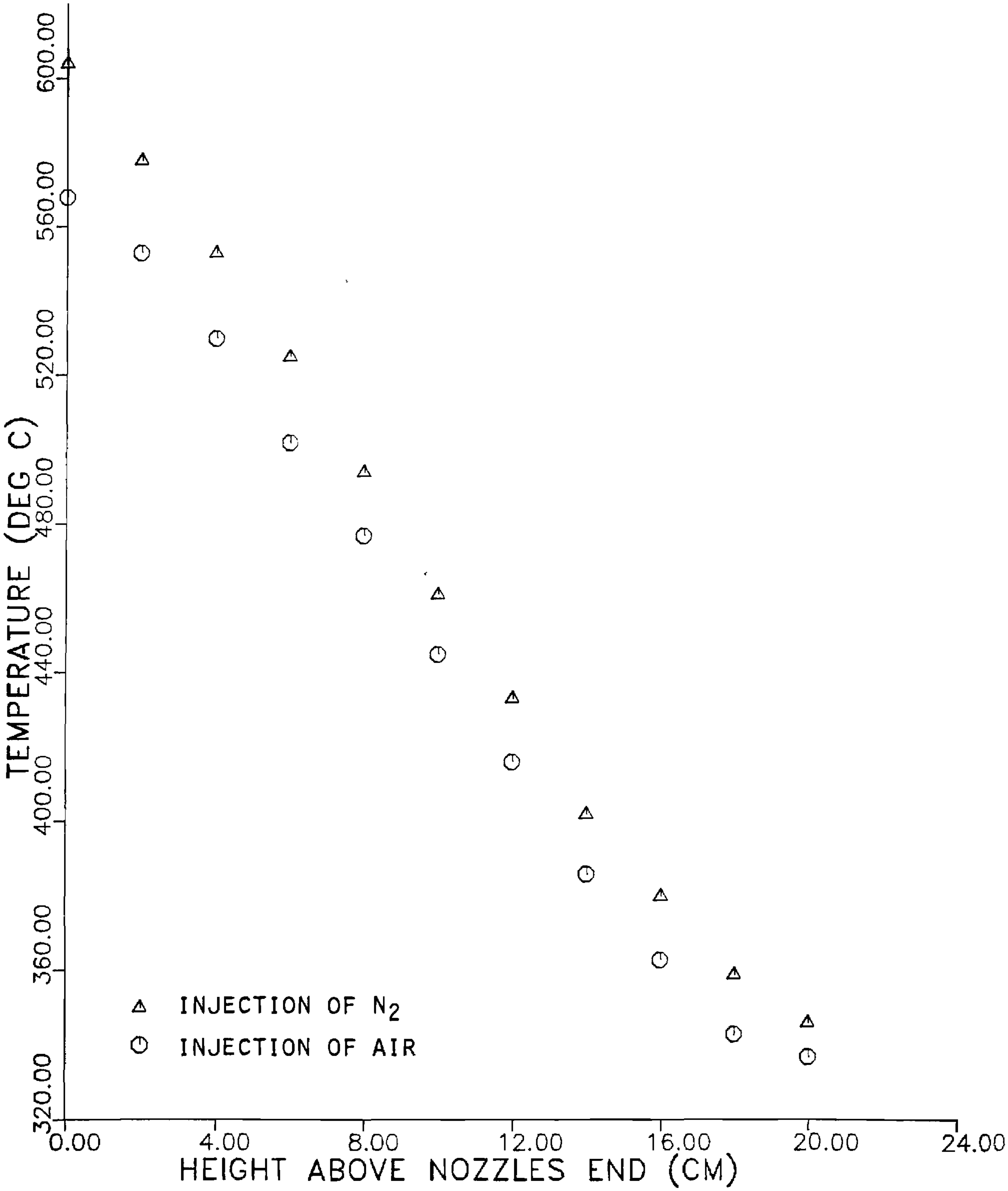
through the Omega Ice-Point Cell. The centerline gas temperatures inside the nozzle were measured by traversing the thermocouple manually and recording its output displayed on the digital millivoltmeter. The thermocouple used in the measurements of temperatures in the reaction zones above the burner matrix was constructed in a Y-shape and mounted on a toothed shaft. This shaft is one of the components of a DISA traversing system. A stepper motor is in turn controlled through a DISA Model 52B01 sweep drive unit. A voltage output from the sweep drive unit was used to drive the X-channel of a Hewlett-Packard, Model 7046A two channel X-Y plotter. The thermocouple output was recorded in mV through the Y-channel of the X-Y plotter.

A PYRO Micro-Optical Pyrometer of Pyrometer Instrument Co., Inc. was also used to estimate the coal particle temperatures. This was carried out only above the burner matrix and outside the injection nozzle as the particles moved upwards.

APPENDIX B

TEMPERATURE PROFILES AND ISOTHERMS

This appendix includes representative temperature profiles, and isotherms in association with measurements carried out on the flat flame burner with the opposed gas-particle jet. Figures B.1-B.3 present axial temperature profiles inside the 1.27 o.d. gas-particle injection nozzle. Figures B.5-B.25 are representative temperature profiles below the gas-particle injection nozzle as well as adjacent to it. Both the 1.27 o.d. and the 2.54 o.d. nozzle are represented at the equivalence ratios of $\phi = 0.67$ and 0.86. Finally Figures B.26-B.31 display isotherms, generated by the computer program, for the 1.27 o.d. nozzle with air and N_2 as the carrier gas and at the two equivalence ratios of $\phi = 0.67$ and 0.86.



B.1. Axial Temperature Profiles Inside 1.27 o.d. Gas-Particle Nozzle of Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 2460$ g/h, Air/N_2 as Carrier Gas, $\dot{m}_{cg} = 54.6$ g/h, Lignite Coal Particles < 53 μm, $\dot{m}_p = 9.6$ g/h.

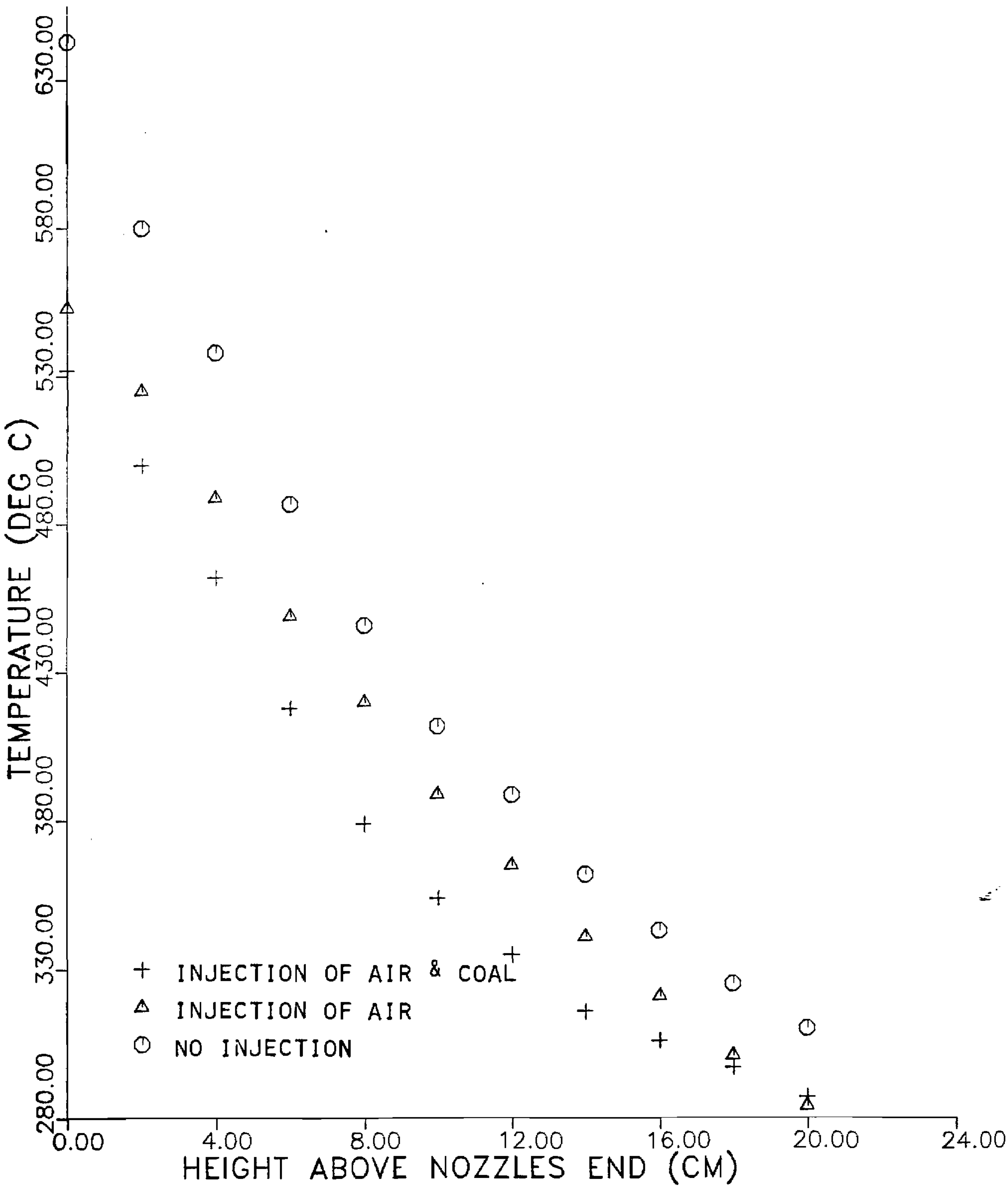


Figure B.2. Axial Temperature Profiles Inside 1.27 o.d. Gas-Particle Nozzle of Flat Flame Burner, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, Air as Carrier Gas, $\dot{m}_{cg}$ = 73.0 g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c$ = 14.4 g/h.

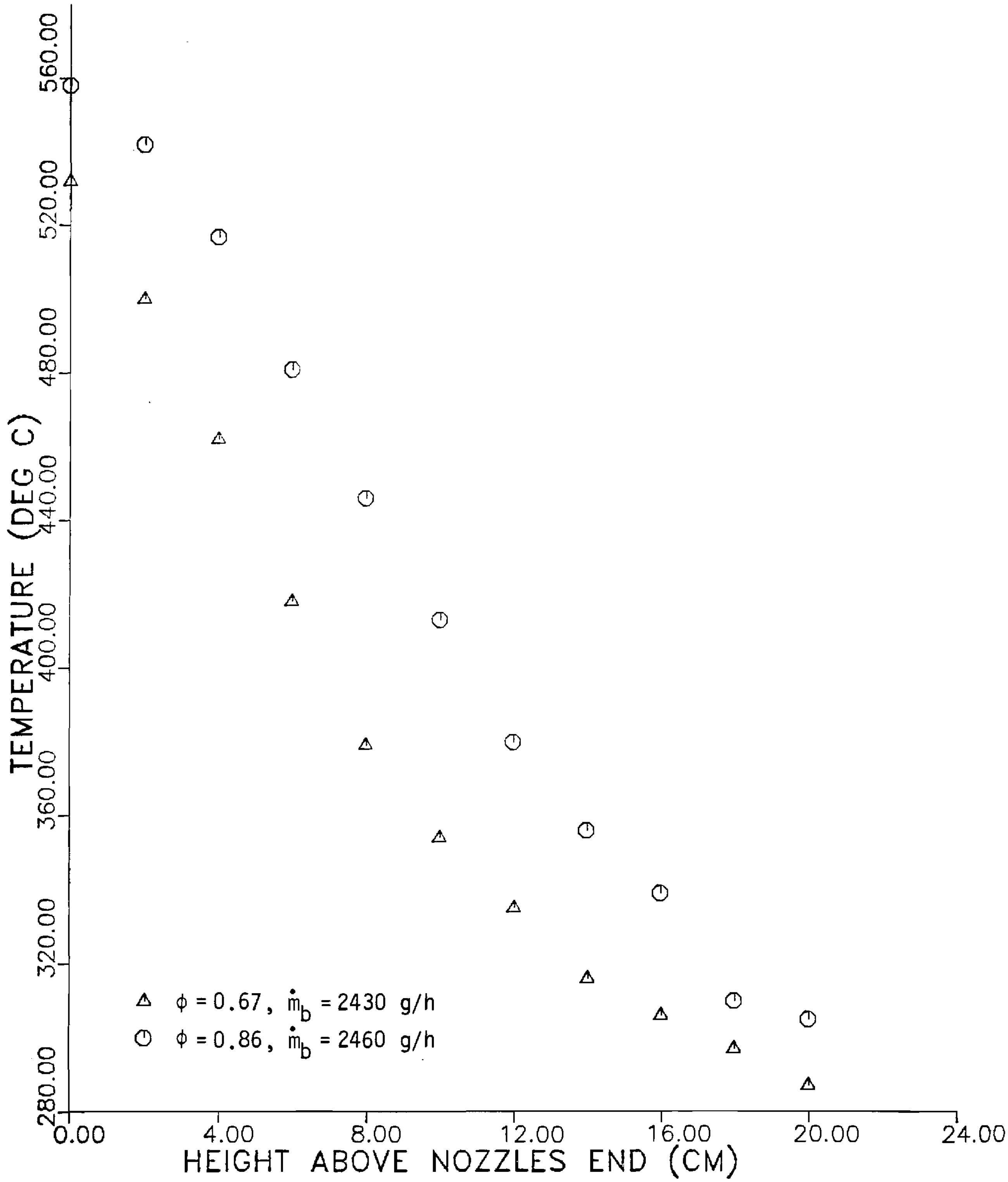


Figure B.3. Axial Temperature Profiles Inside 1.27 o.d. Gas-Particle Nozzle of Flat Flame Burner, Air as Carrier Gas, $\dot{m}_{cg}$ = 73.1 g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c$ = 15.6 g/h.

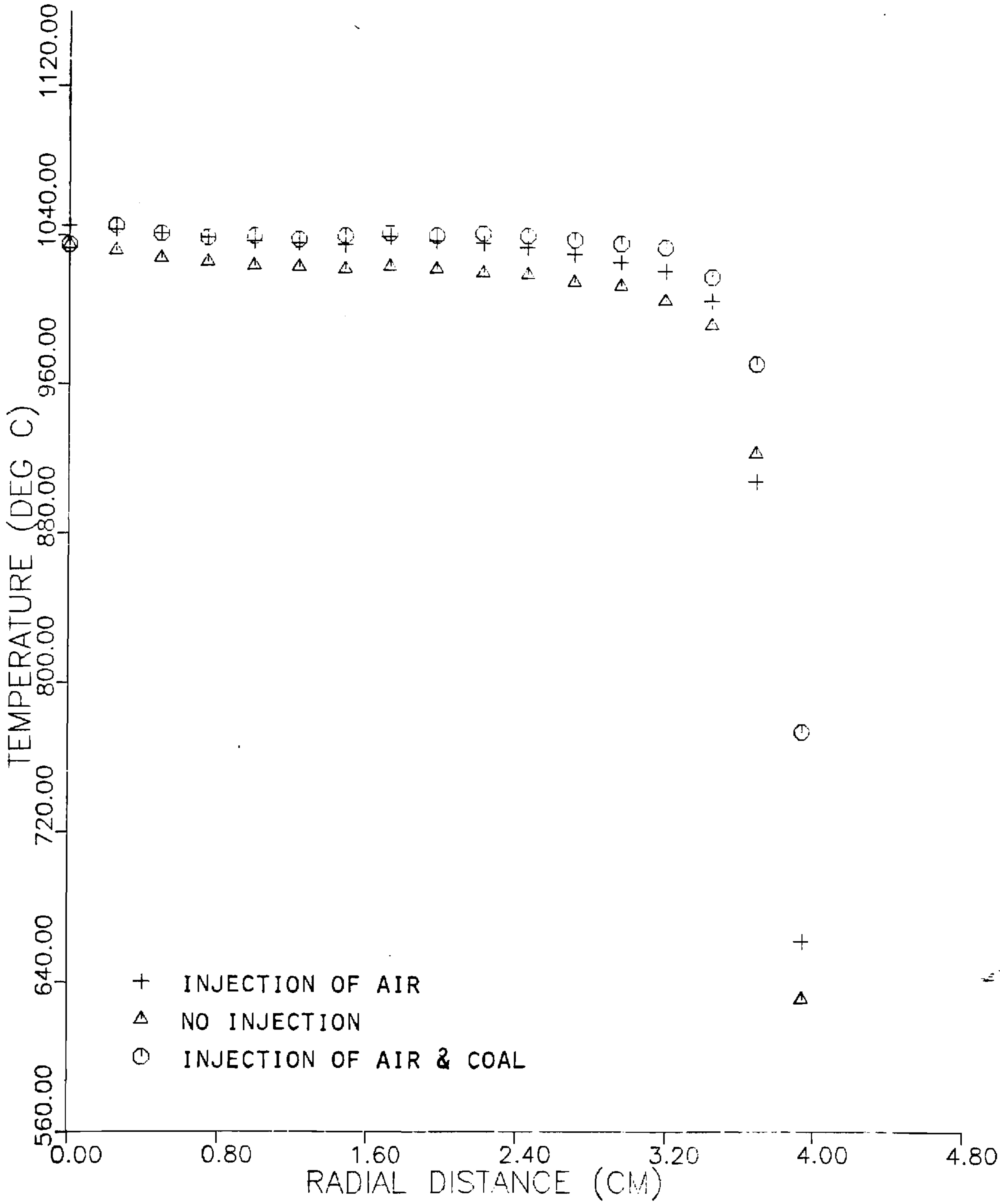


Figure B.4. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 189$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 0.3 cm.

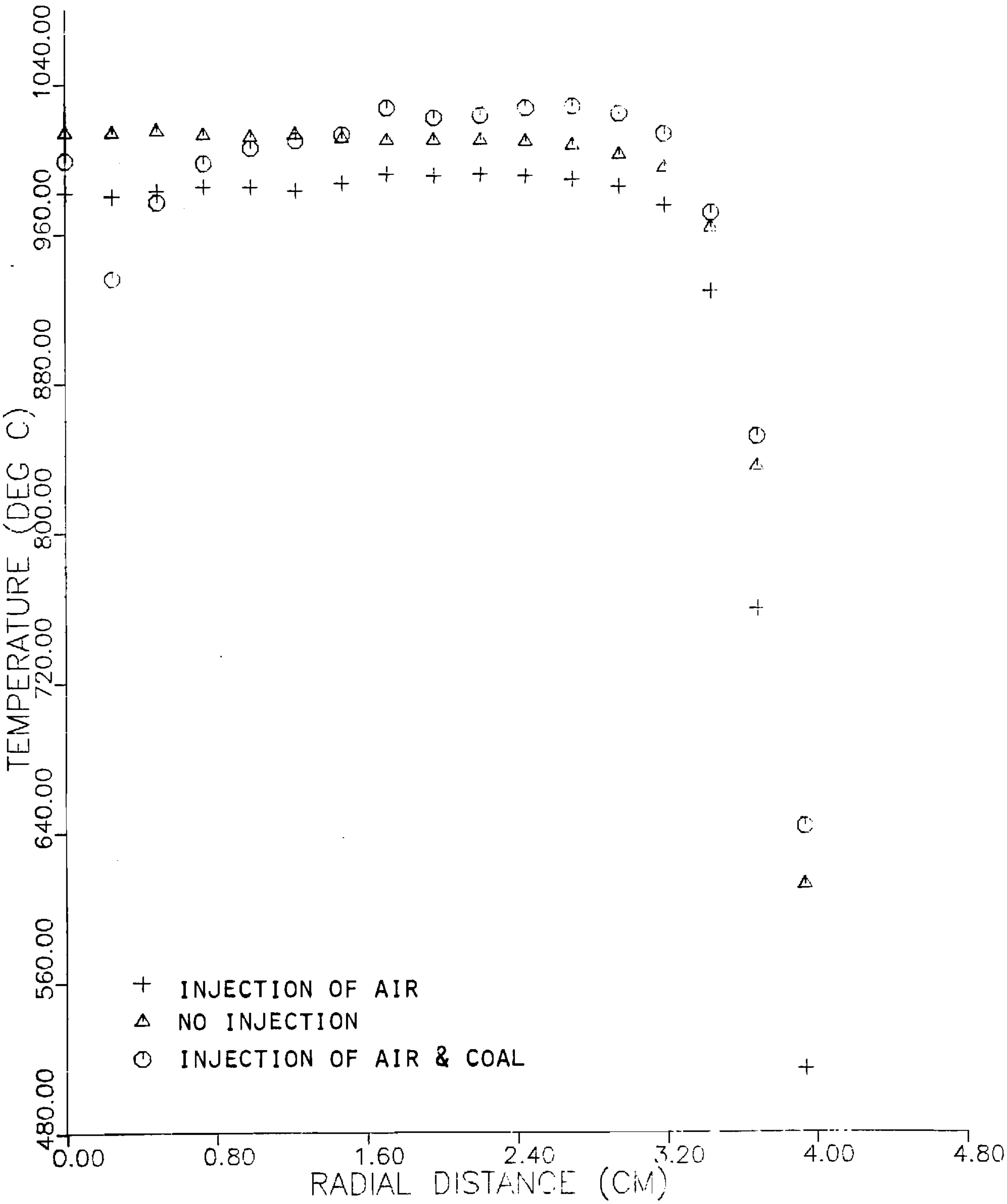


Figure B.5. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 189$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 0.8 cm.

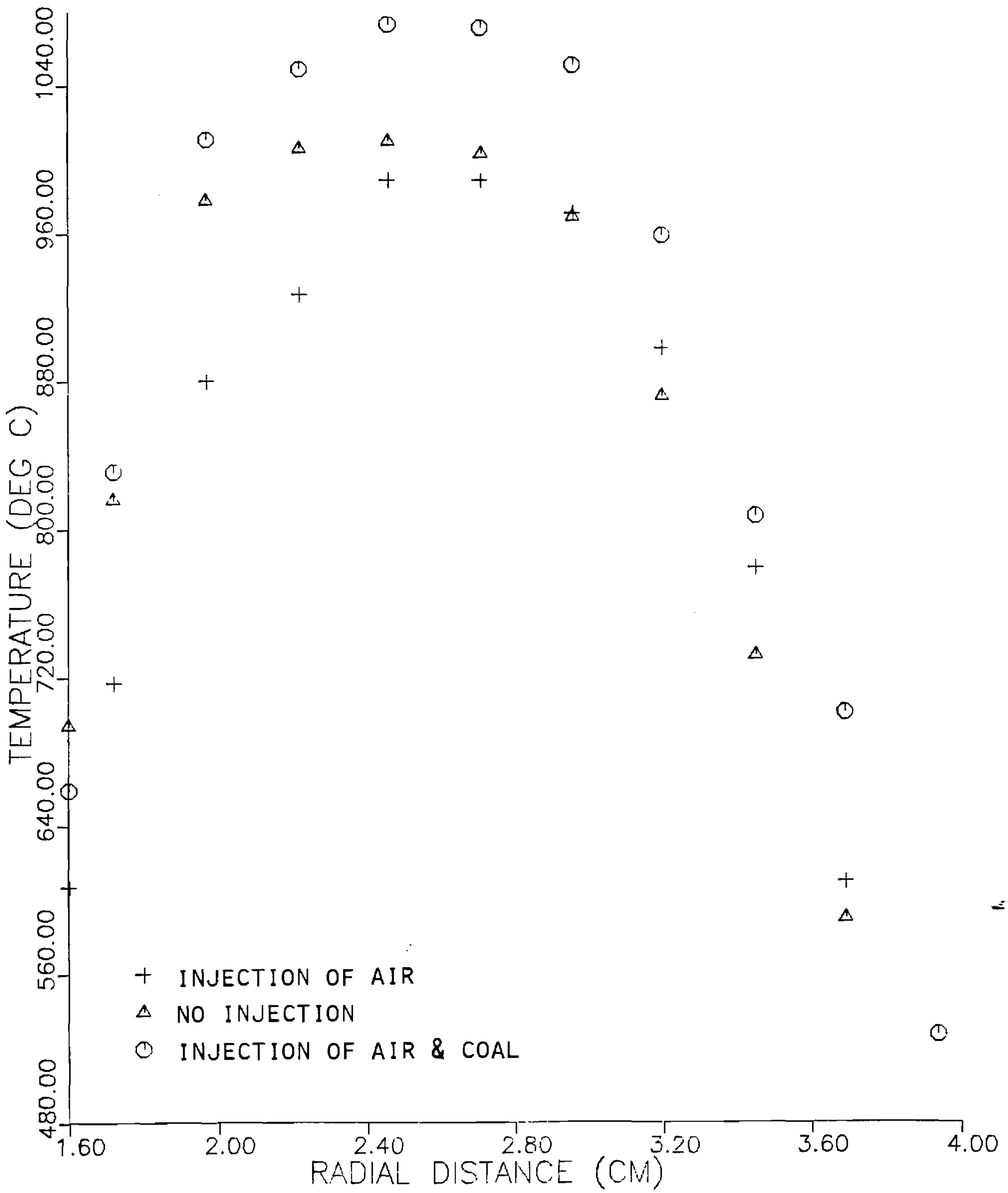


Figure B.6. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 189$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 2.3 cm.

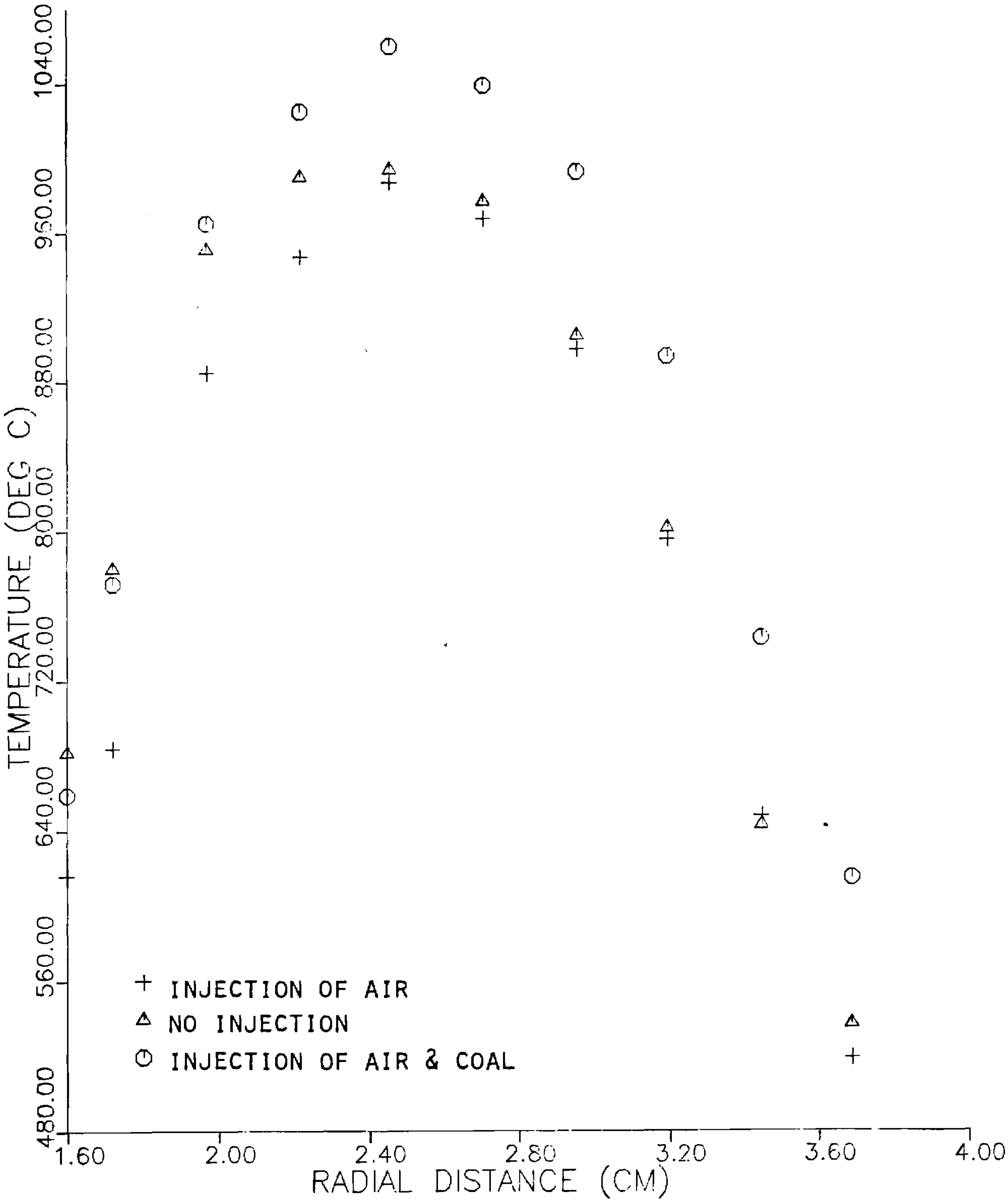


Figure B.7. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg}$ = 189 g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 15.0 g/h, Height Above Burner Matrix H = 2.8 cm.

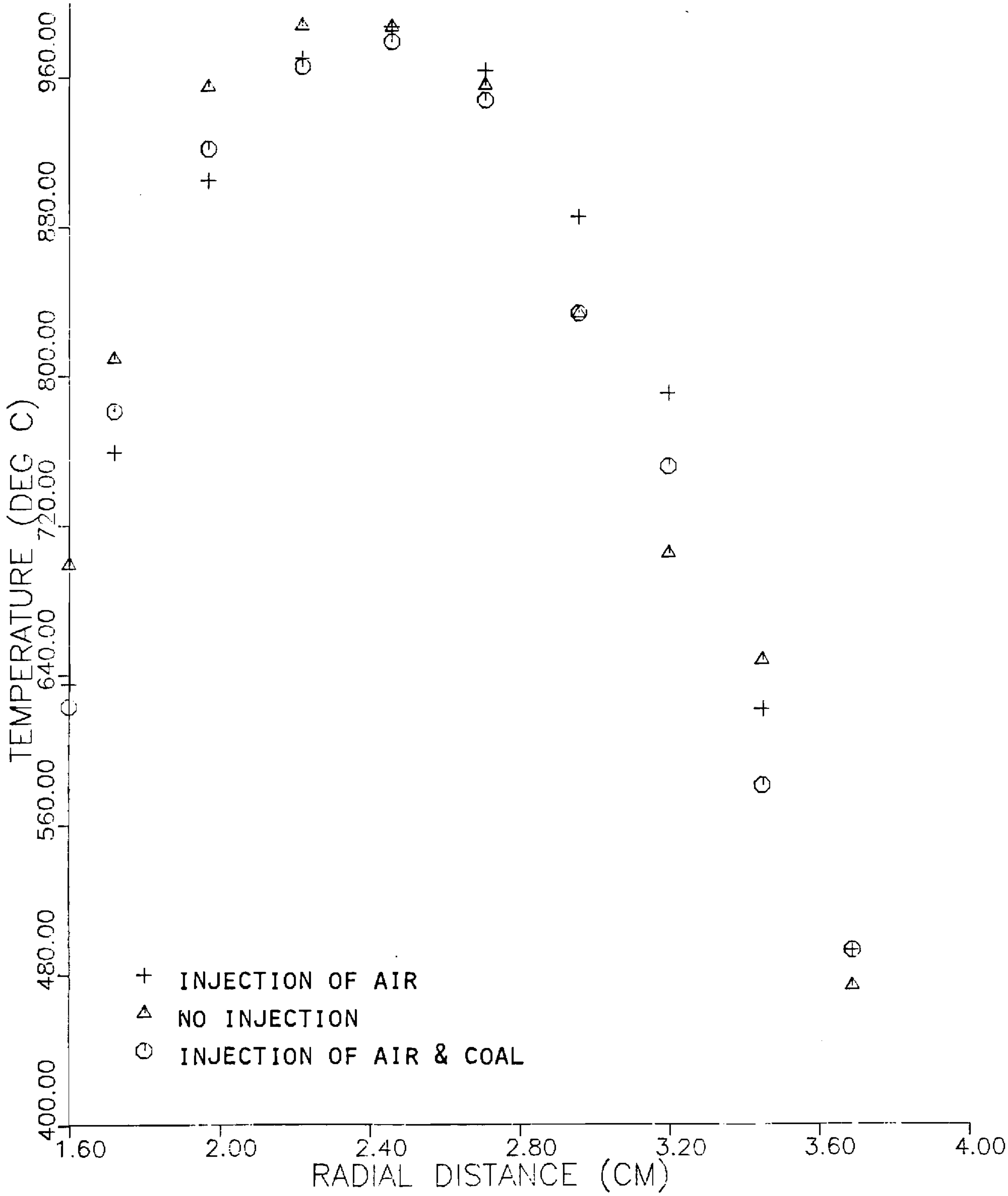


Figure B.8. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg}$ = 189 g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 15.0 g/h, Height Above Burner Matrix H = 3.3 cm.

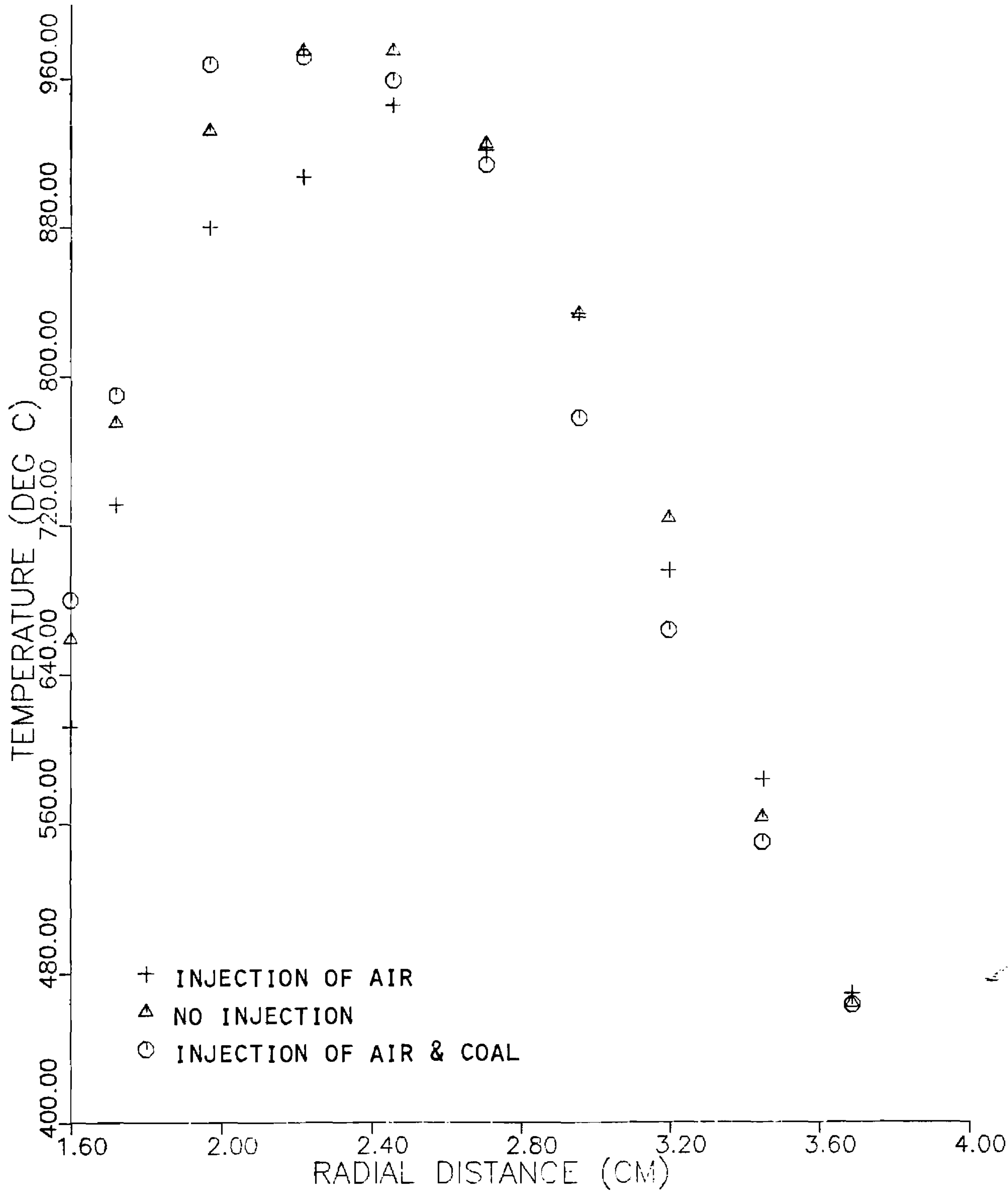


Figure B.9. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 189$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 3.8 cm.

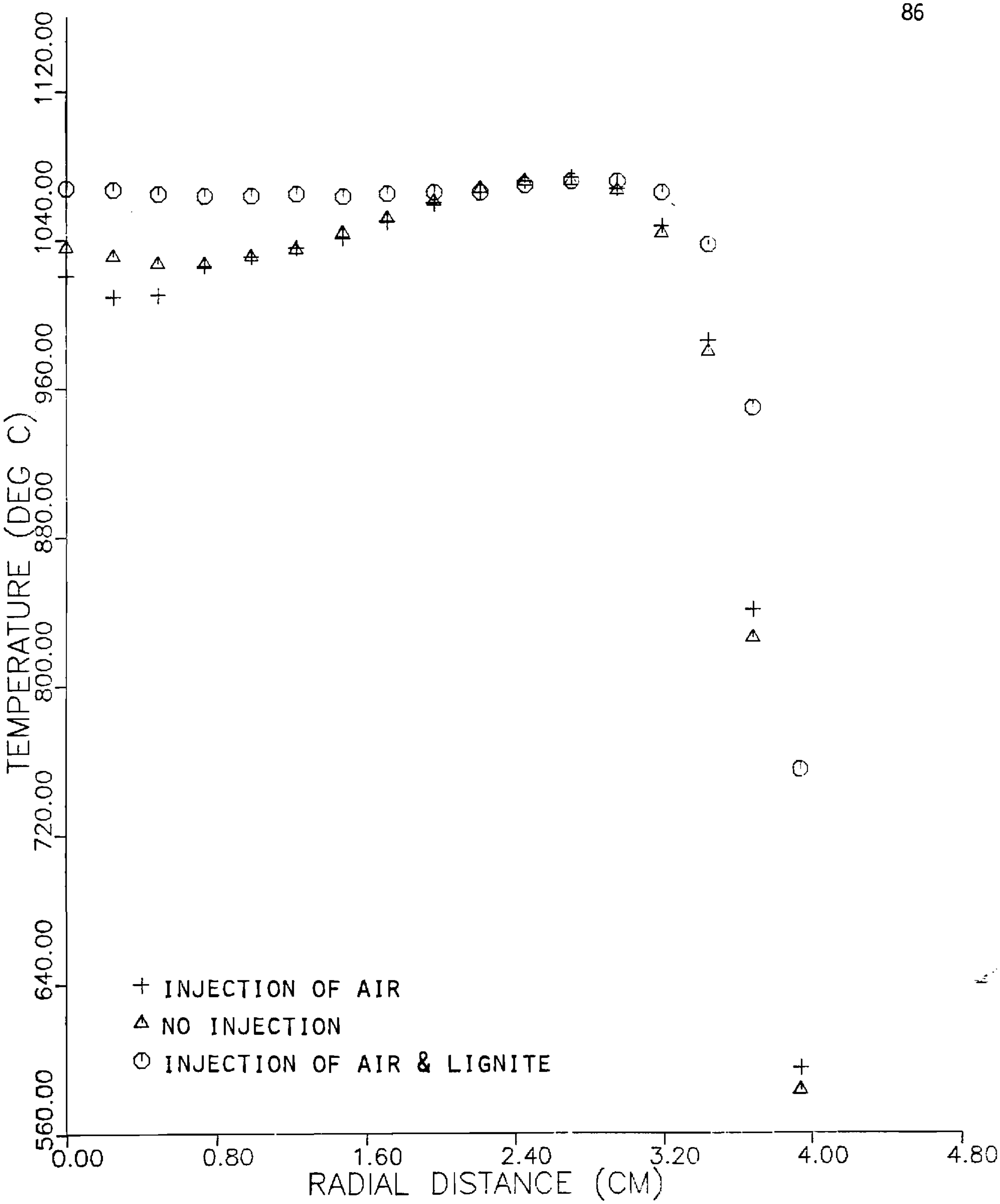


Figure B.10. Temperature Profiles in the Reaction Zone of the Flat Flame Burner ϕ = 0.86, $\dot{m}_b$ = 2454 g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg}$ = 84.8 g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 27.6 g/h, Height Above Burner Matrix H = 0.8 cm.

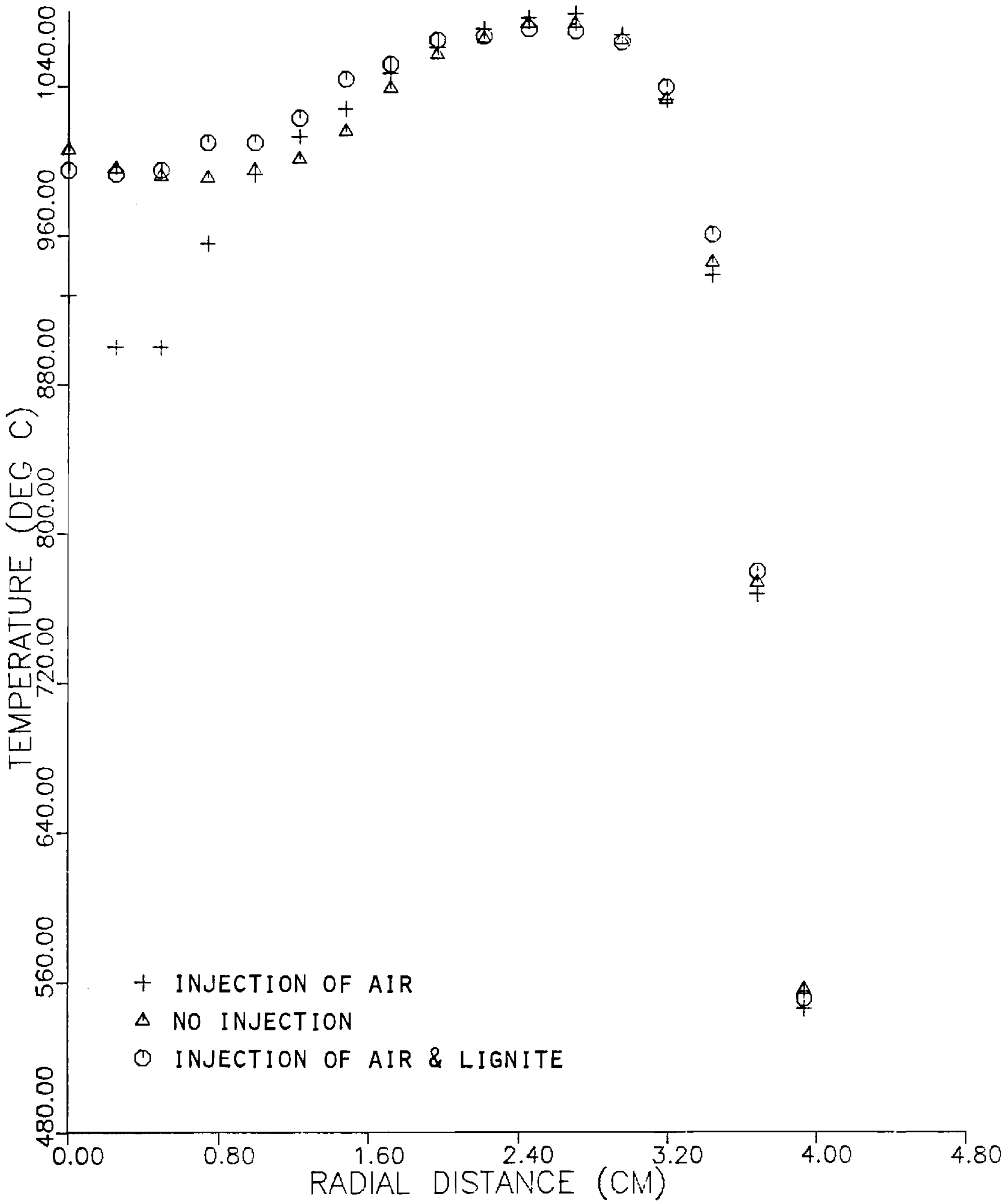


Figure B.11. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 2454$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 84.8$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 27.6$ g/h, Height Above Burner Matrix H = 1.3 cm.

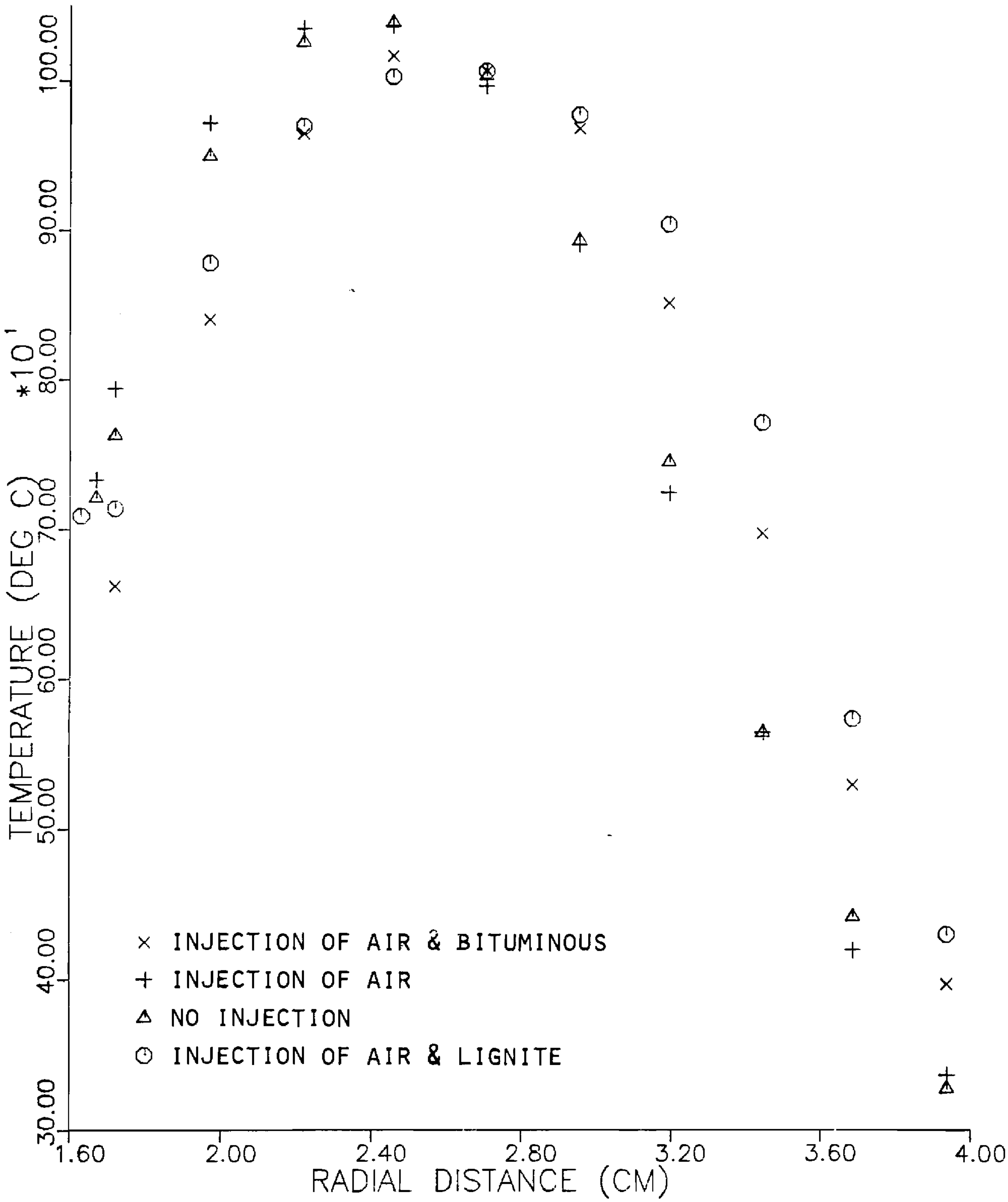


Figure B.12. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 2454$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 84.8$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 27.6$ g/h, Height Above Burner Matrix H = 3.3 cm.

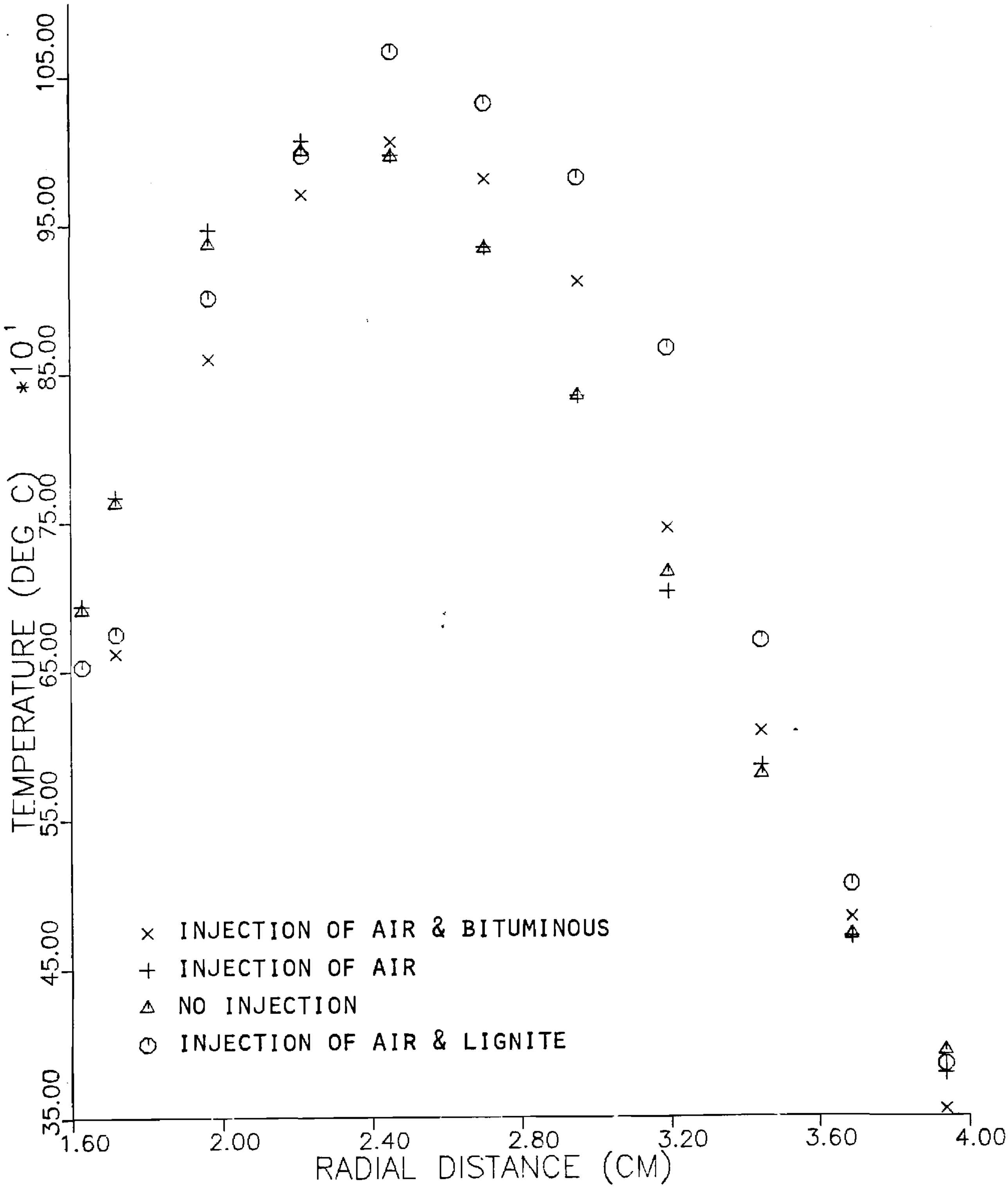


Figure B.13. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 2454$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 84.8$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 27.6$ g/h, Height Above Burner Matrix H = 3.8 cm.

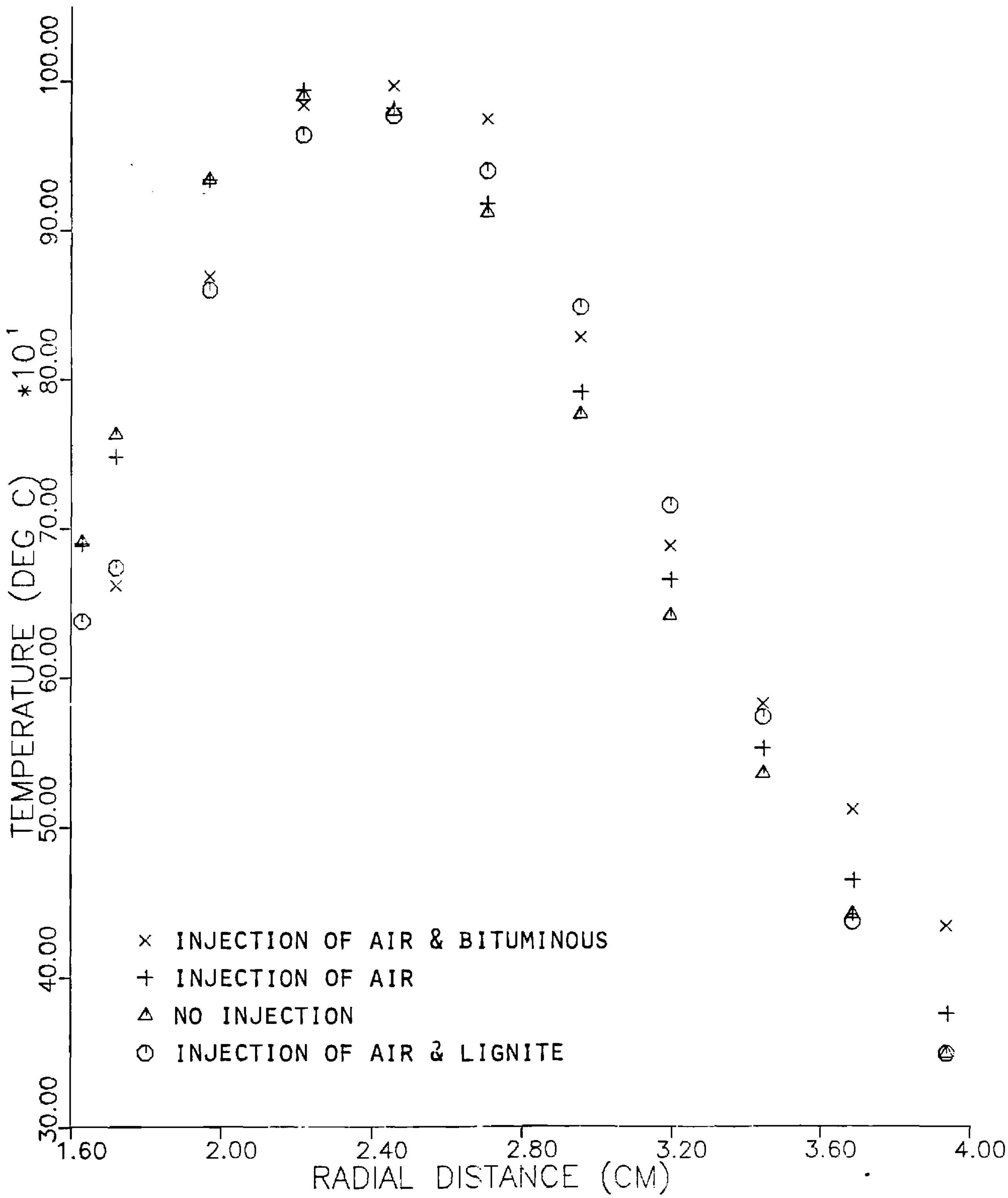


Figure B.14. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.86$, $\dot{m}_b = 2454$ g/h, 2.54 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 84.8$ g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c = 27.6$ g/h, Height Above Burner Matrix H = 4.3 cm.

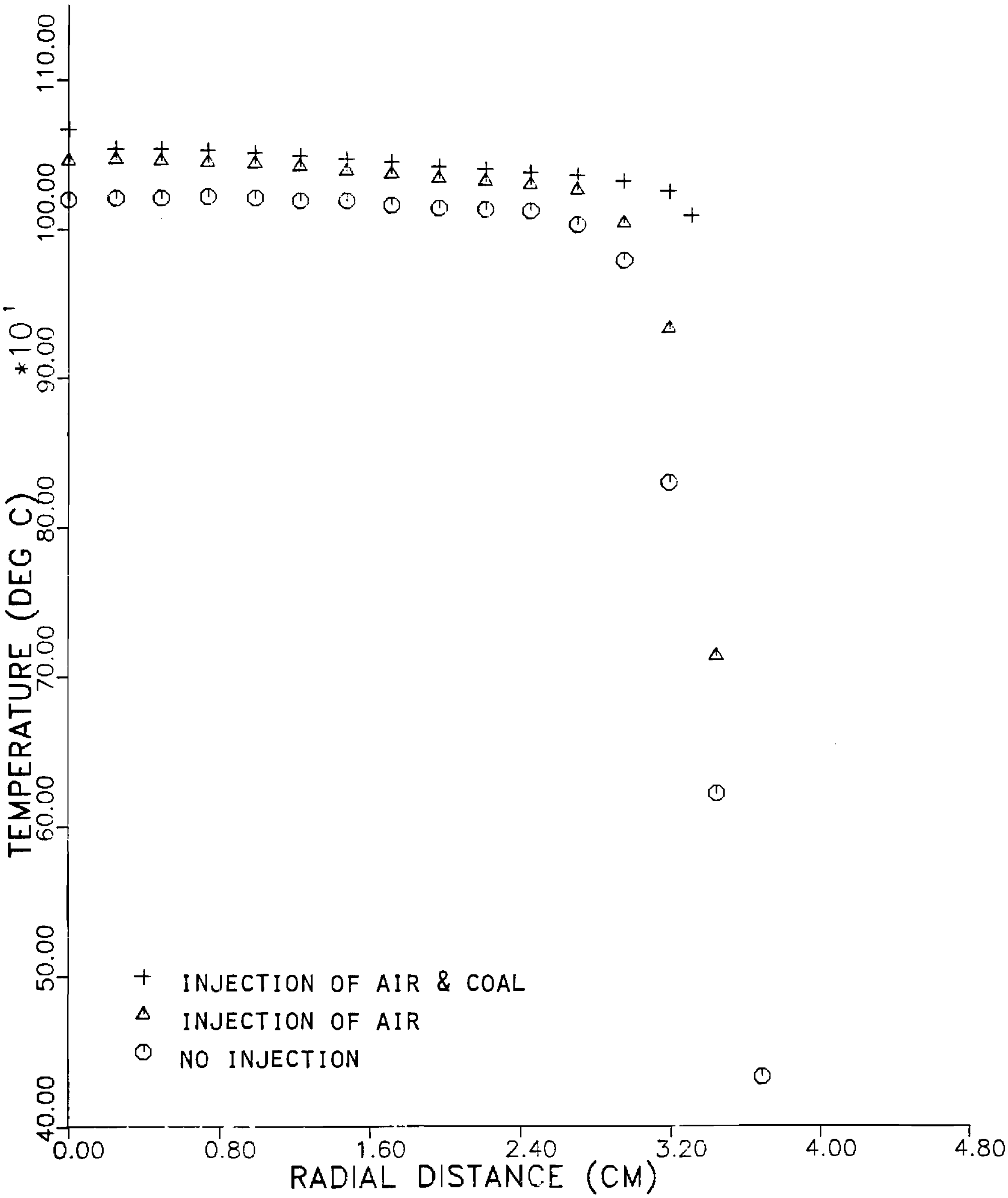


Figure B.15. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 73.0$ g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 1.3 cm.

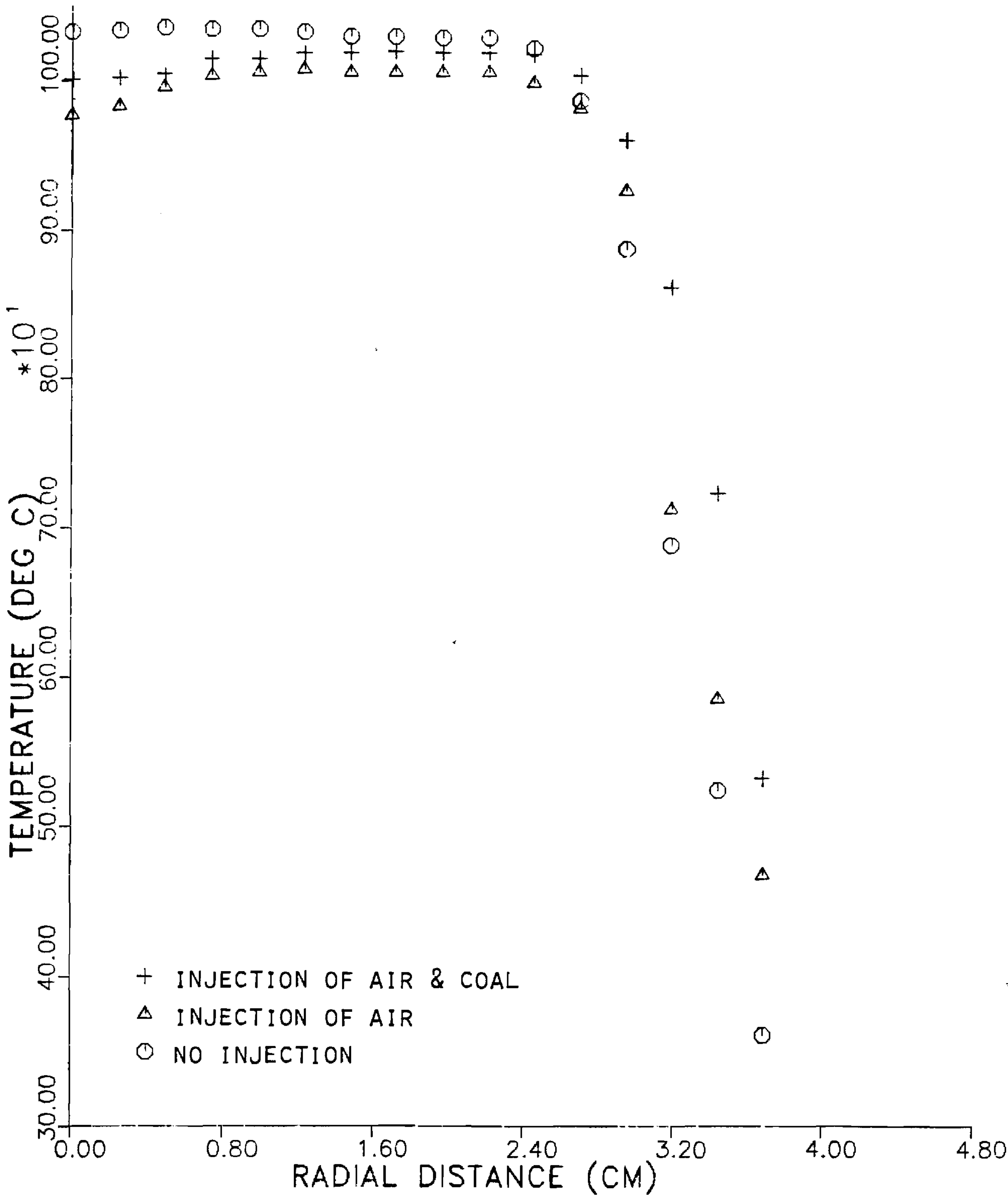


Figure B.16. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 73.0$ g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 1.8 cm.

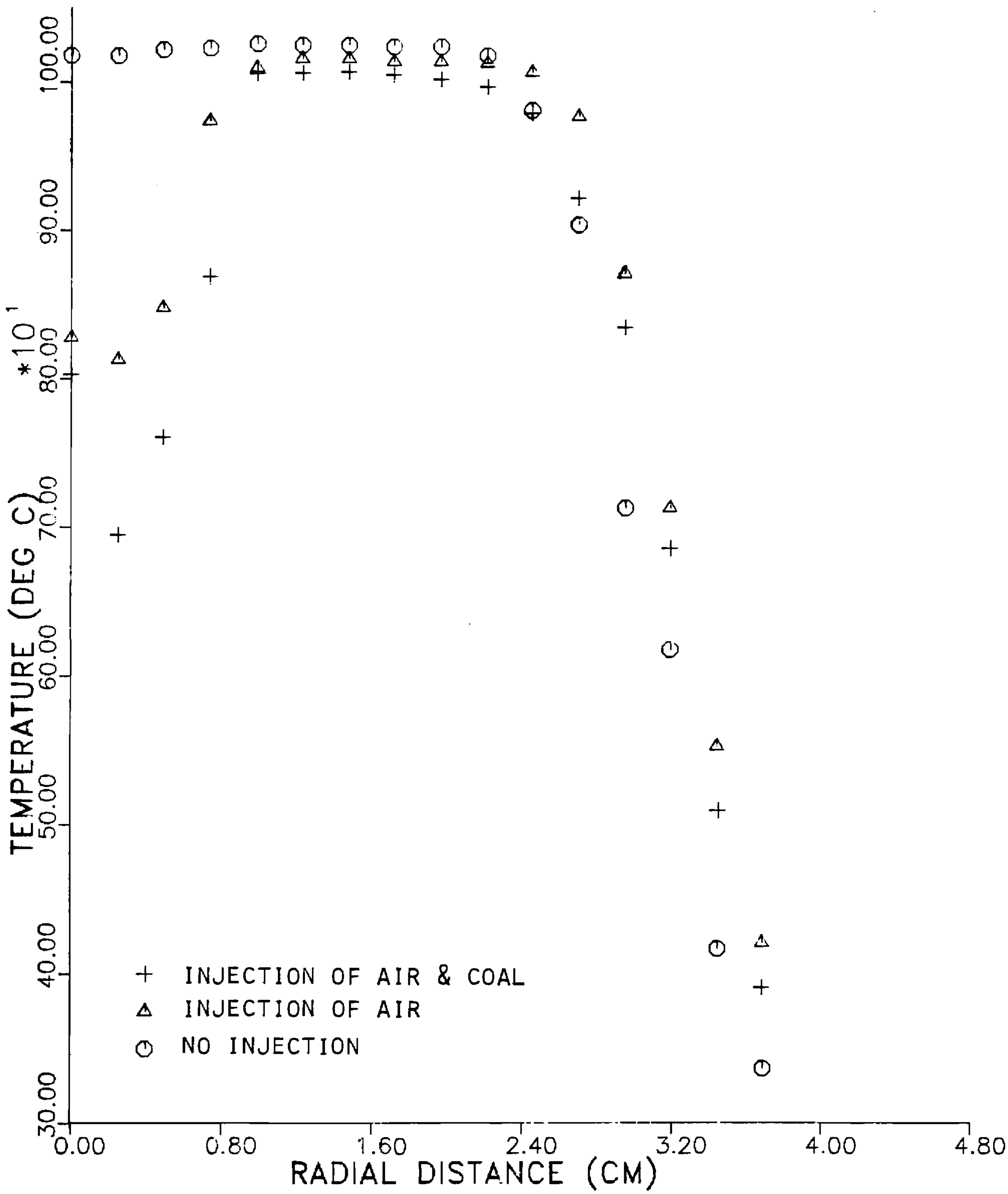


Figure B.17. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg}$ = 73.0 g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c$ = 15.0 g/h, Height Above Burner Matrix H = 2.3 cm.

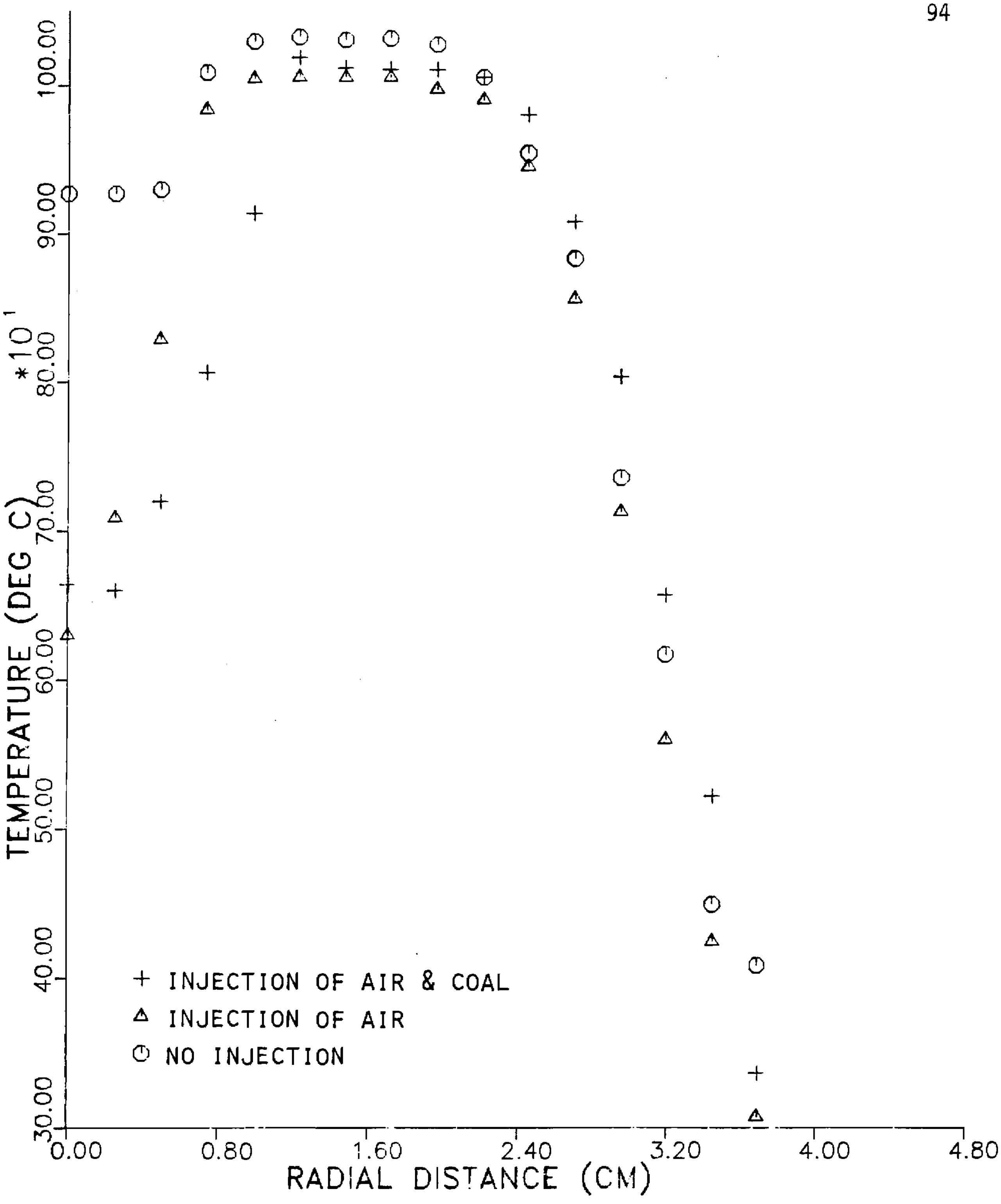


Figure B.18. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 73.0$ g/h, Lignite Coal Particles < 53 μm, Height Above Burner Matrix H = 2.8 cm.

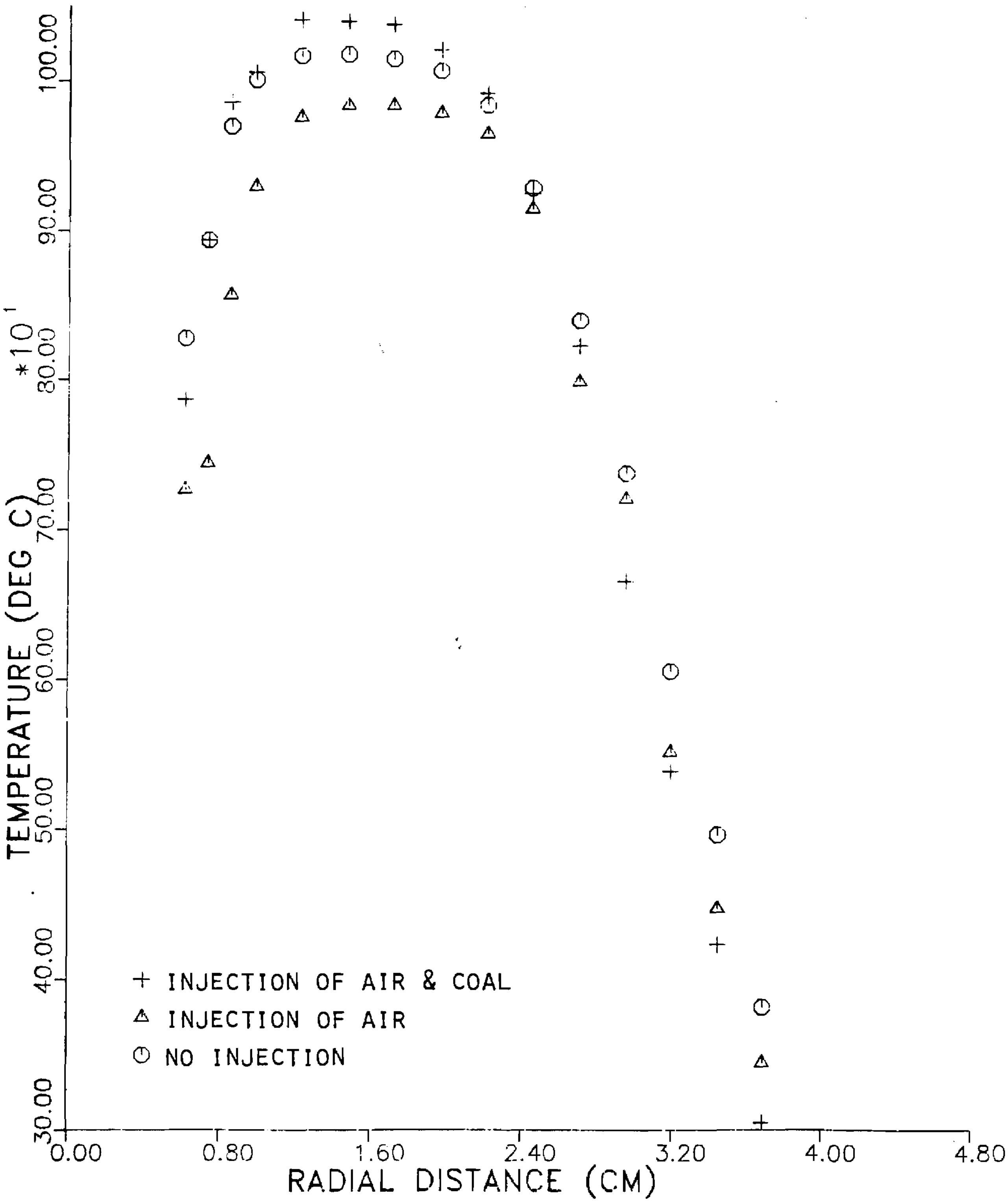


Figure B.19. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 1.27 o.d., Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 73.0$ g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 3.3 cm.

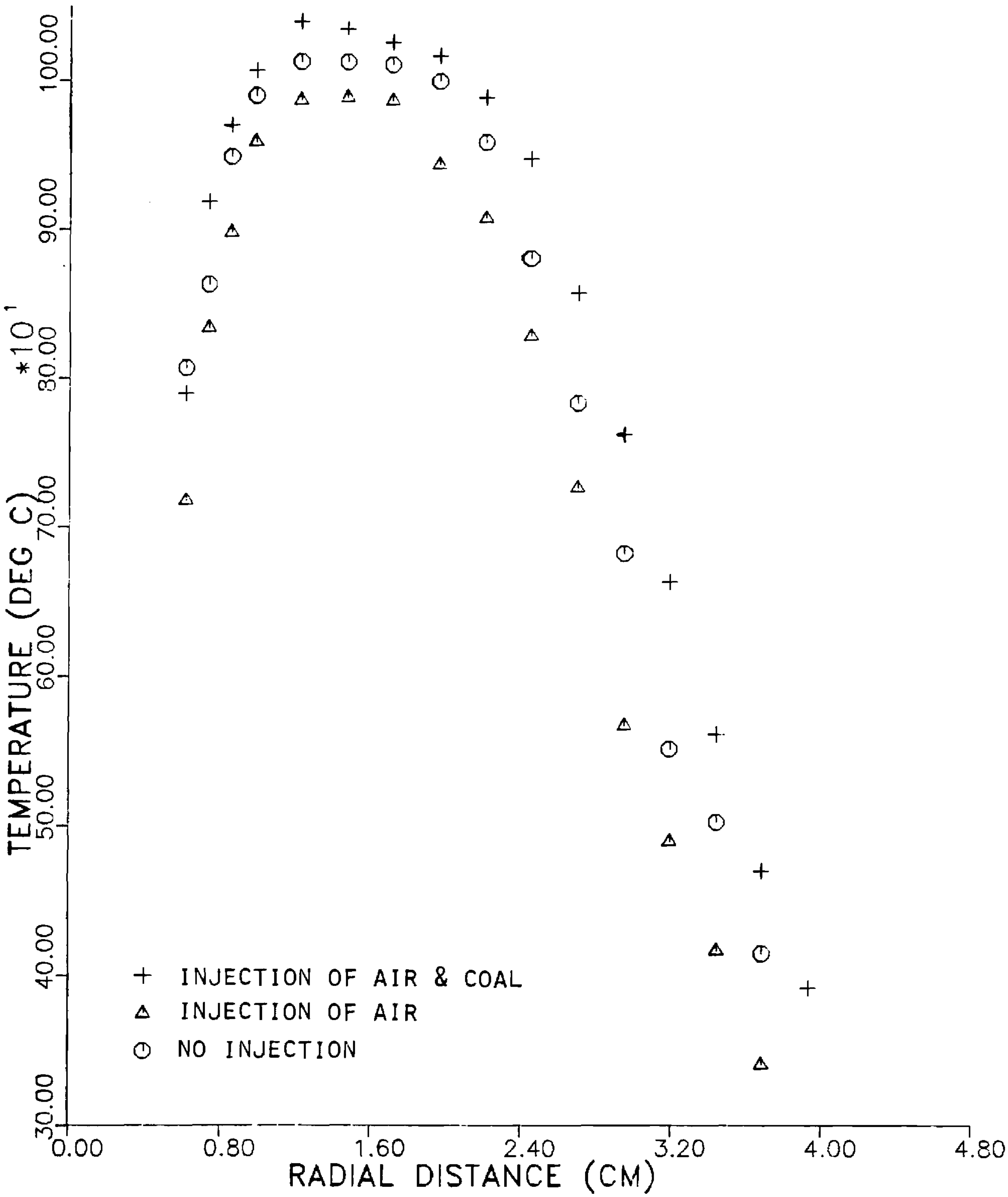


Figure B.20. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg}$ = 73.0 g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c$ = 15.0 g/h, Height Above Burner Matrix H = 3.8 cm.

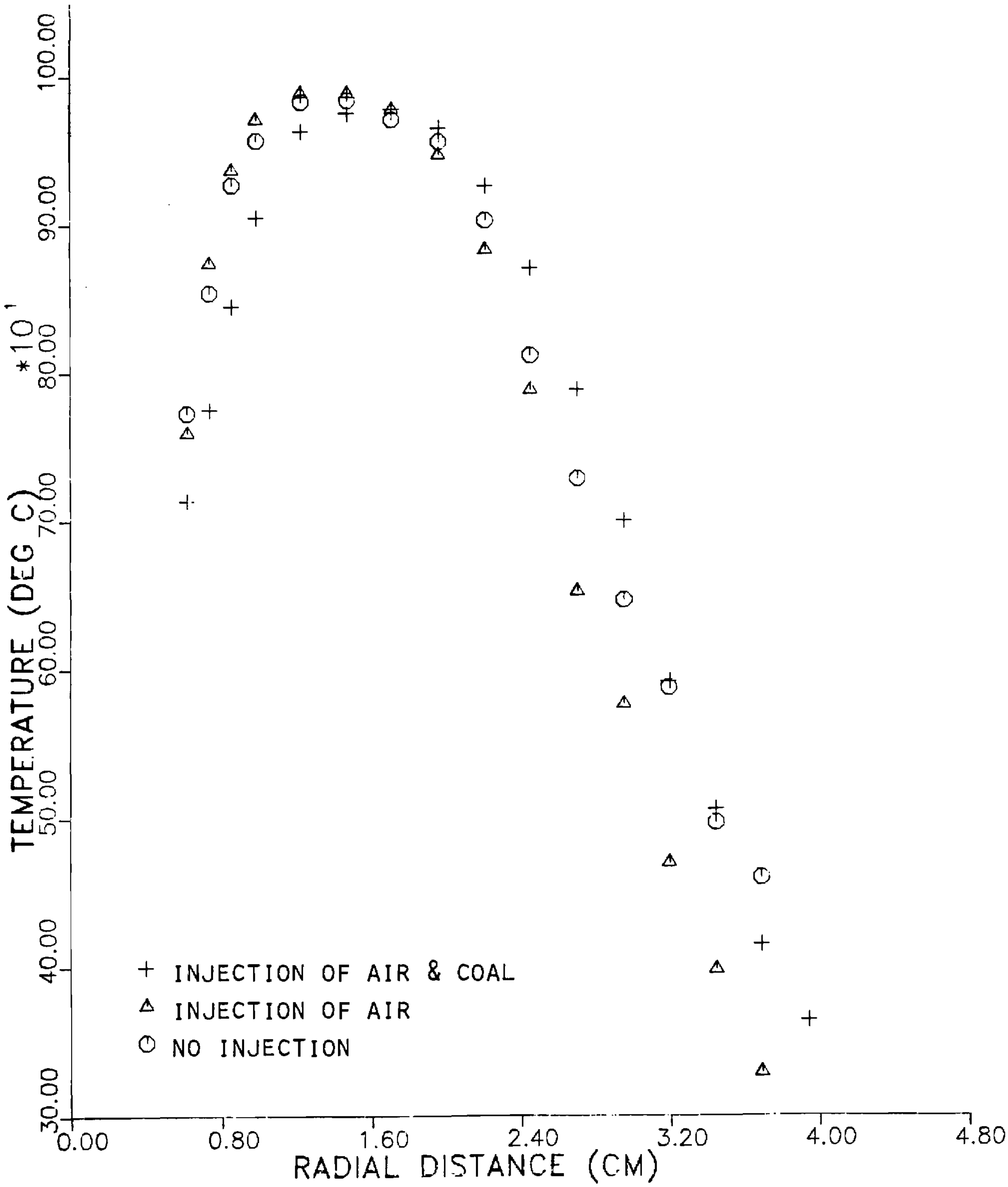


Figure B.21. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air as Carrier Gas, $\dot{m}_{cg} = 73.0$ g/h, Lignite Coal Particles < 53 μm, $\dot{m}_c = 15.0$ g/h, Height Above Burner Matrix H = 4.3 cm.

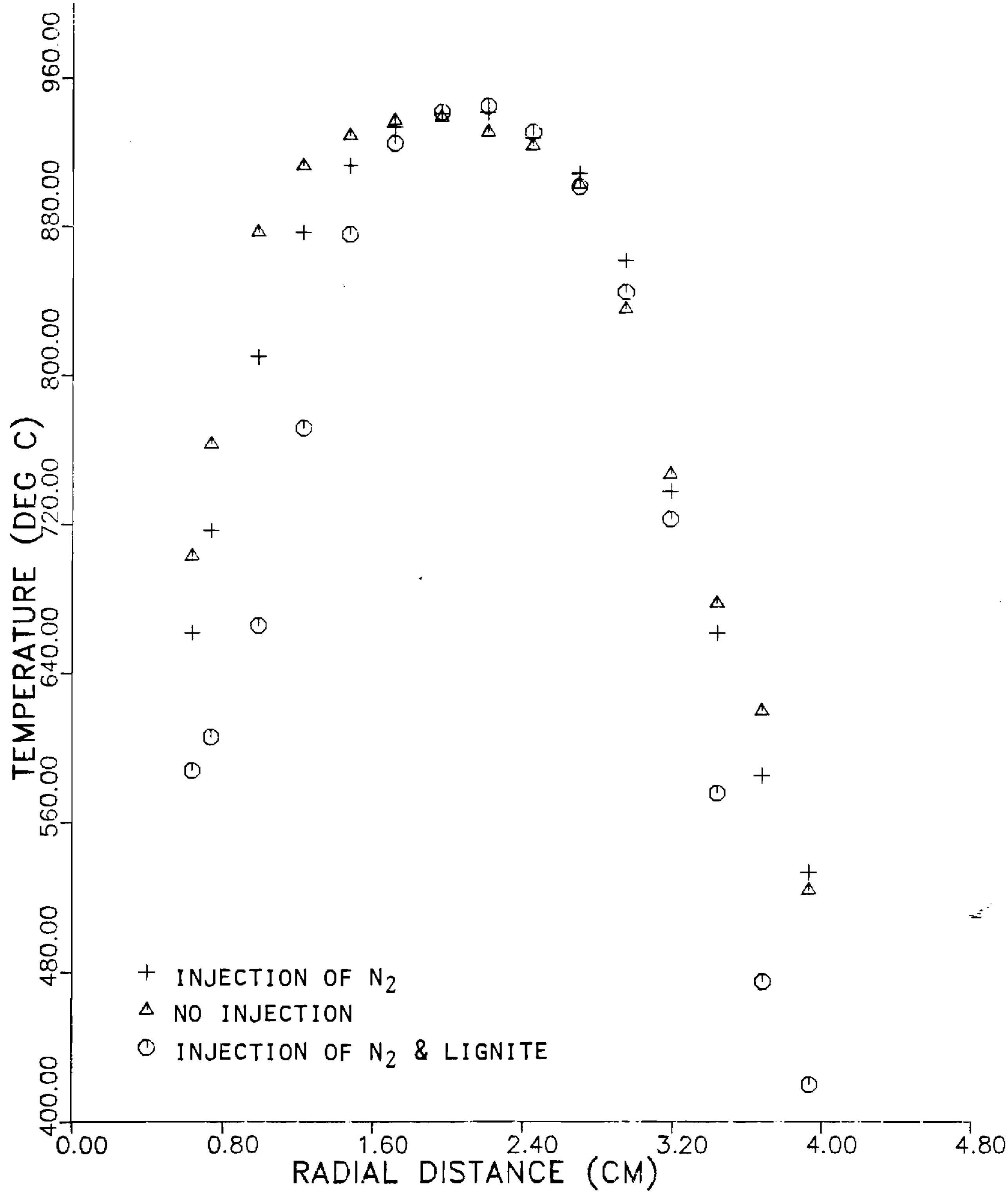


Figure B.22. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.87, m_b = 1883 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, N_2 as Carrier Gas, $\dot{m}_{cg}$ = 37.8 g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 6.6 g/h, Height Above Burner Matrix H = 2.3 cm.

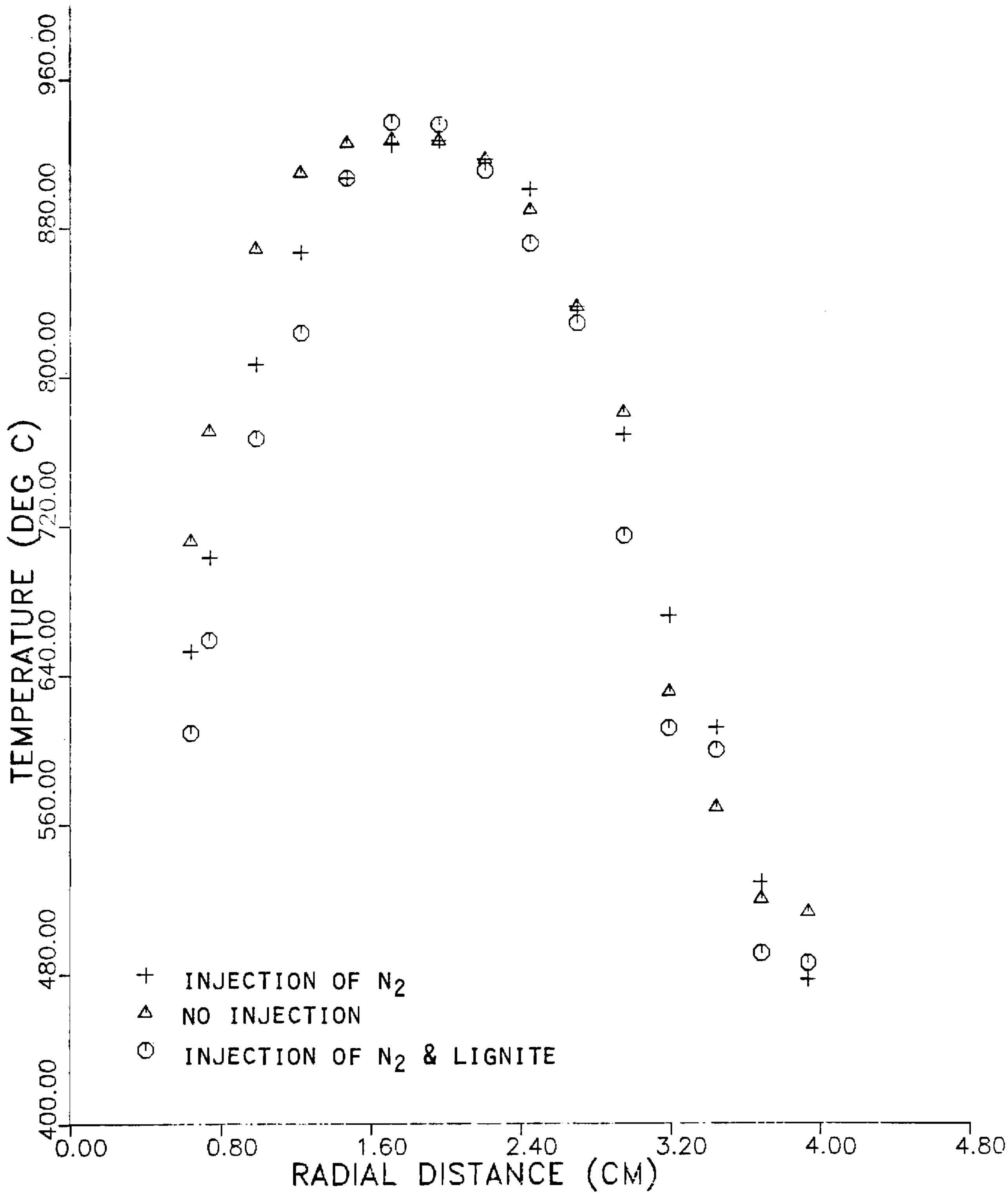


Figure B.23. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.87, $\dot{m}_b$ = 1883 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, N_2 as Carrier Gas, $\dot{m}_{cg}$ = 37.8 g/h, Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 6.6 g/h, Height Above Burner Matrix Height H = 2.8 cm.

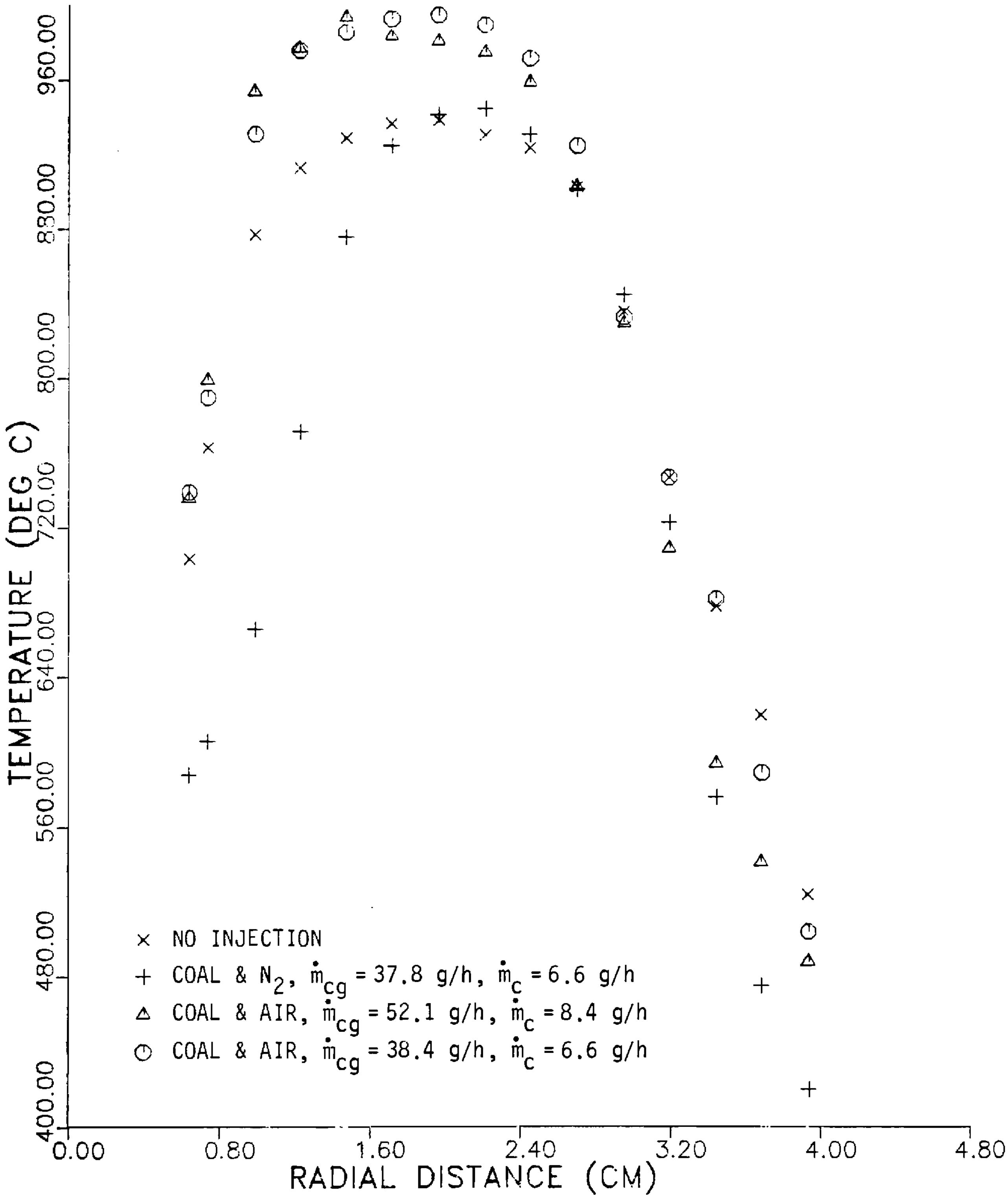


Figure B.24. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.86, $\dot{m}_b$ = 1883 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air/N_2 as Carrier Gas, Lignite Coal Particles 53-74 μm, Height Above Burner Matrix H = 2.3 cm.

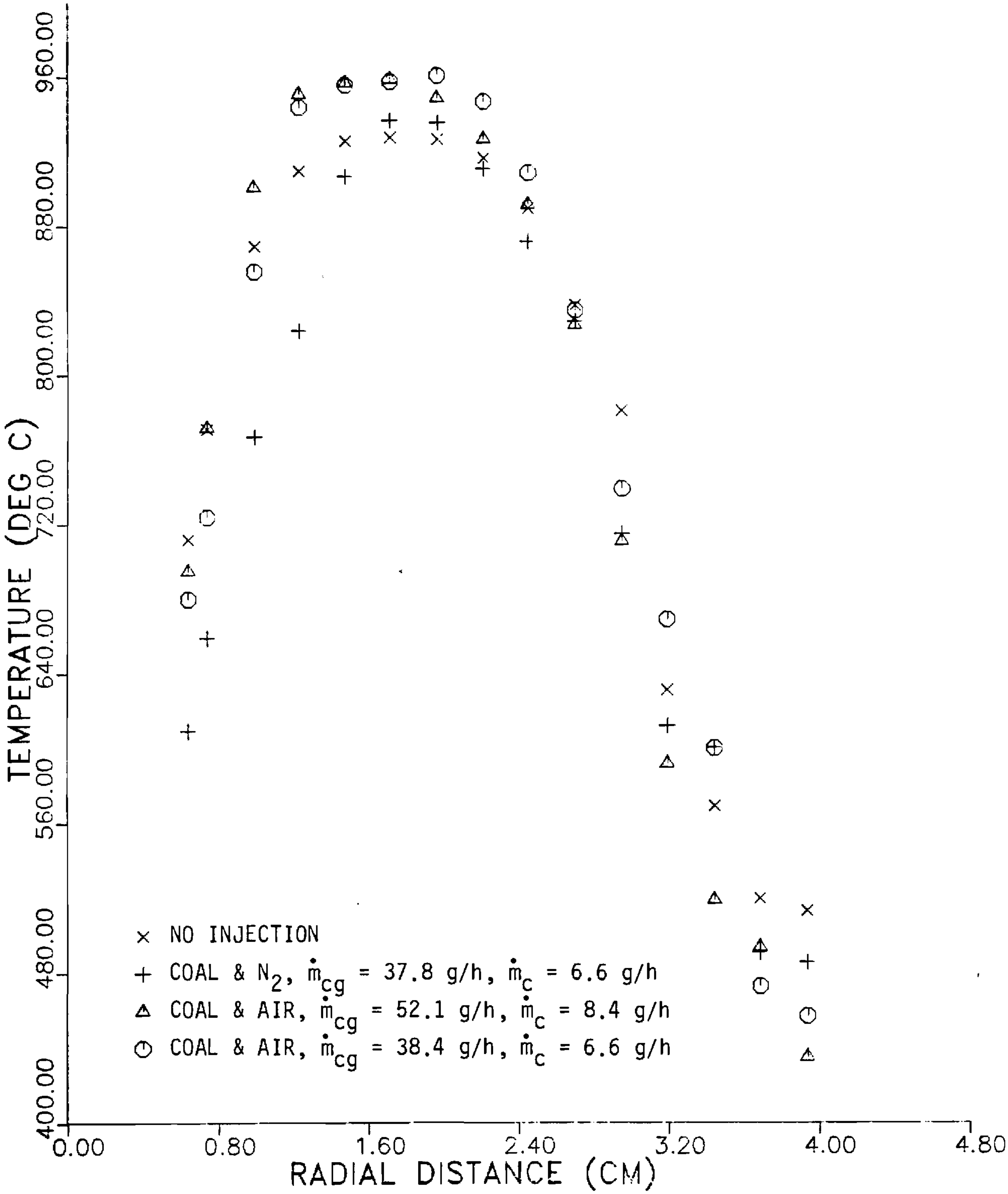


Figure B.25. Temperature Profiles in the Reaction Zone of the Flat Flame Burner, ϕ = 0.86, $\dot{m}_b$ = 1883 g/h, 1.27 o.d. Gas-Particle Injection Nozzle, Air/N_2 as Carrier Gas, Lignite Coal Particles 53-74 μm, Height Above Burner Matrix H = 2.8 cm.

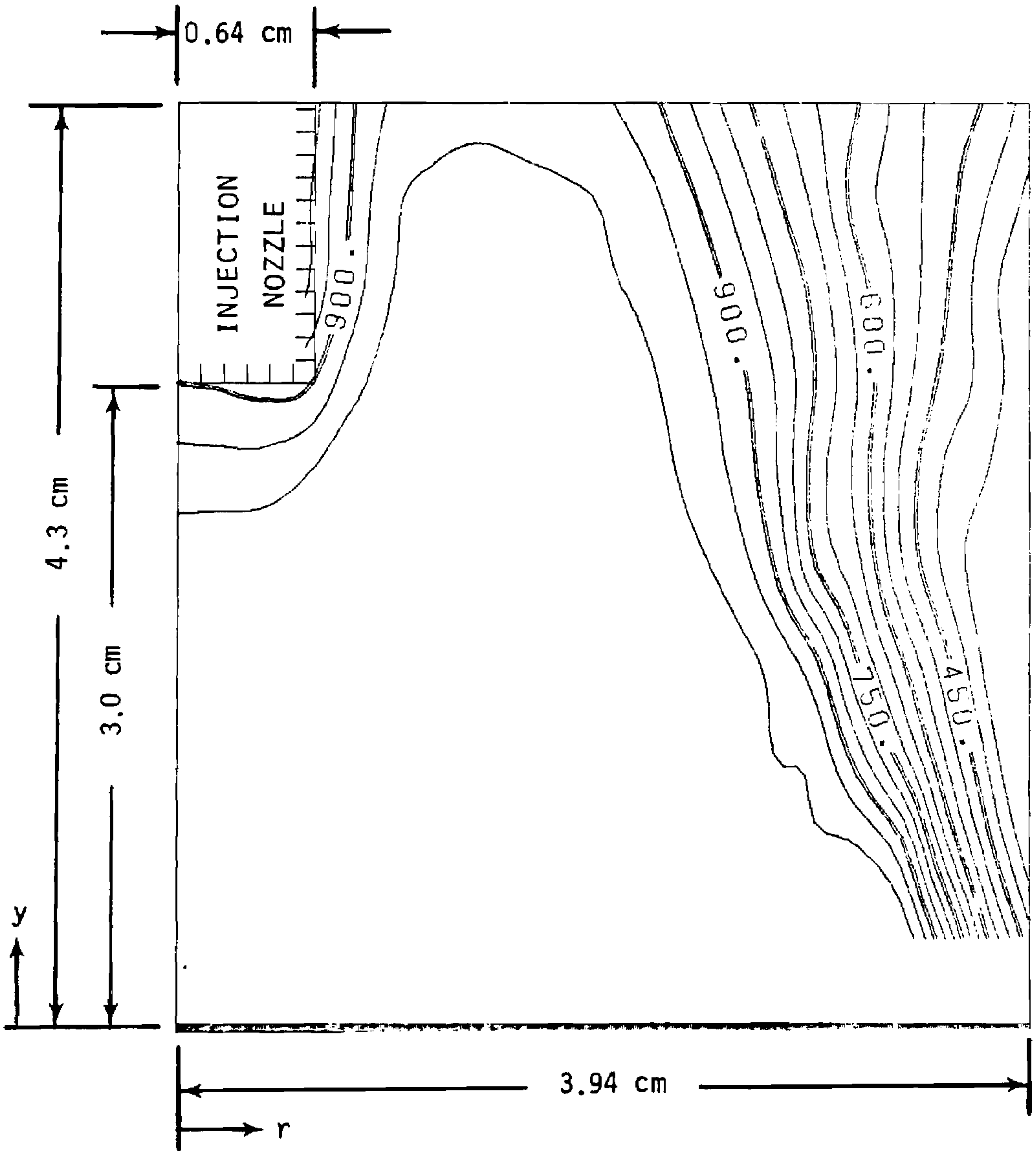


Figure B.26. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h Without Injection.

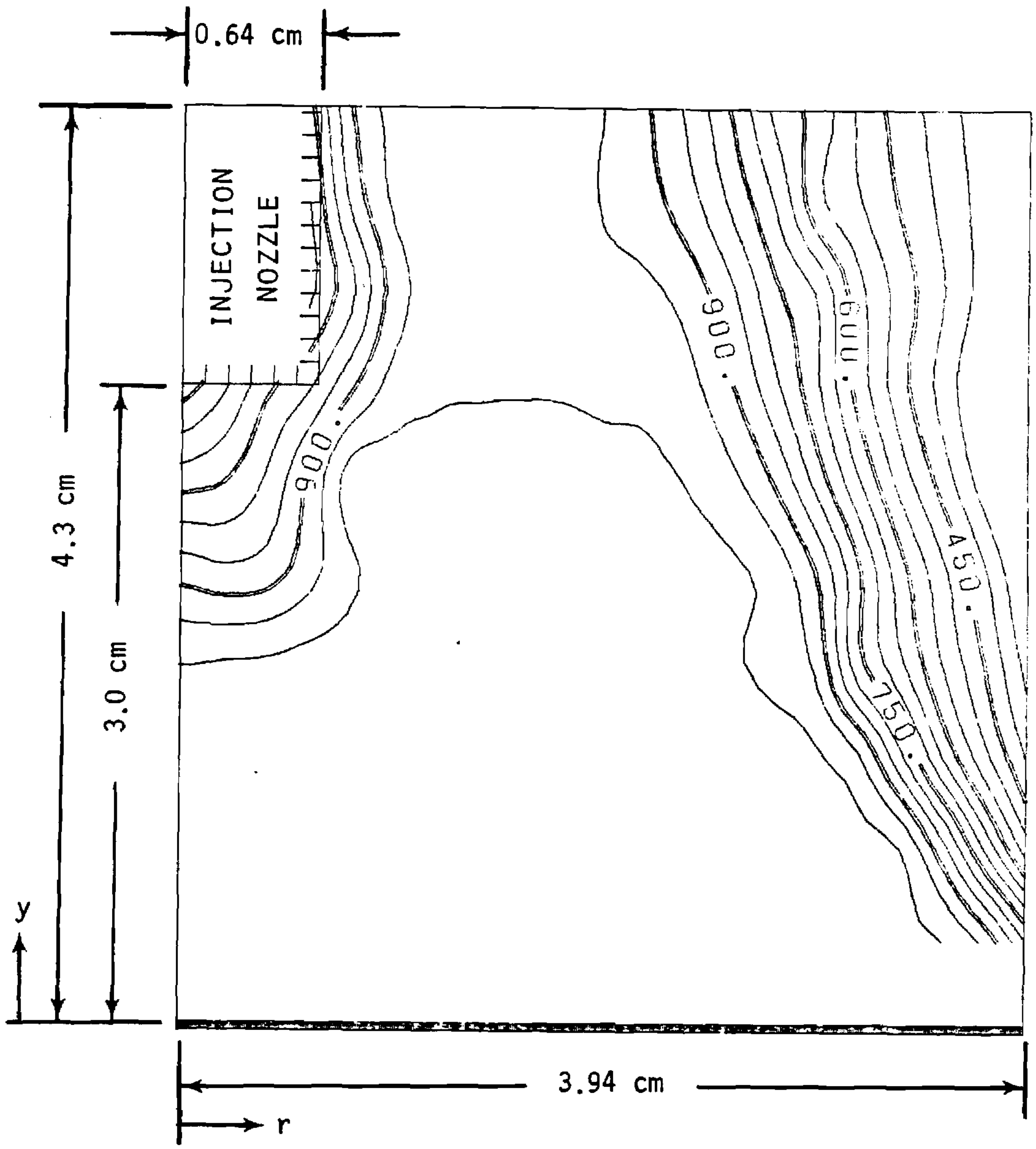


Figure B.27. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, $\phi = 0.67$, $\dot{m}_b = 2430$ g/h, With Injection of Air, $\dot{m}_{cg} = 72.8$ g/h.

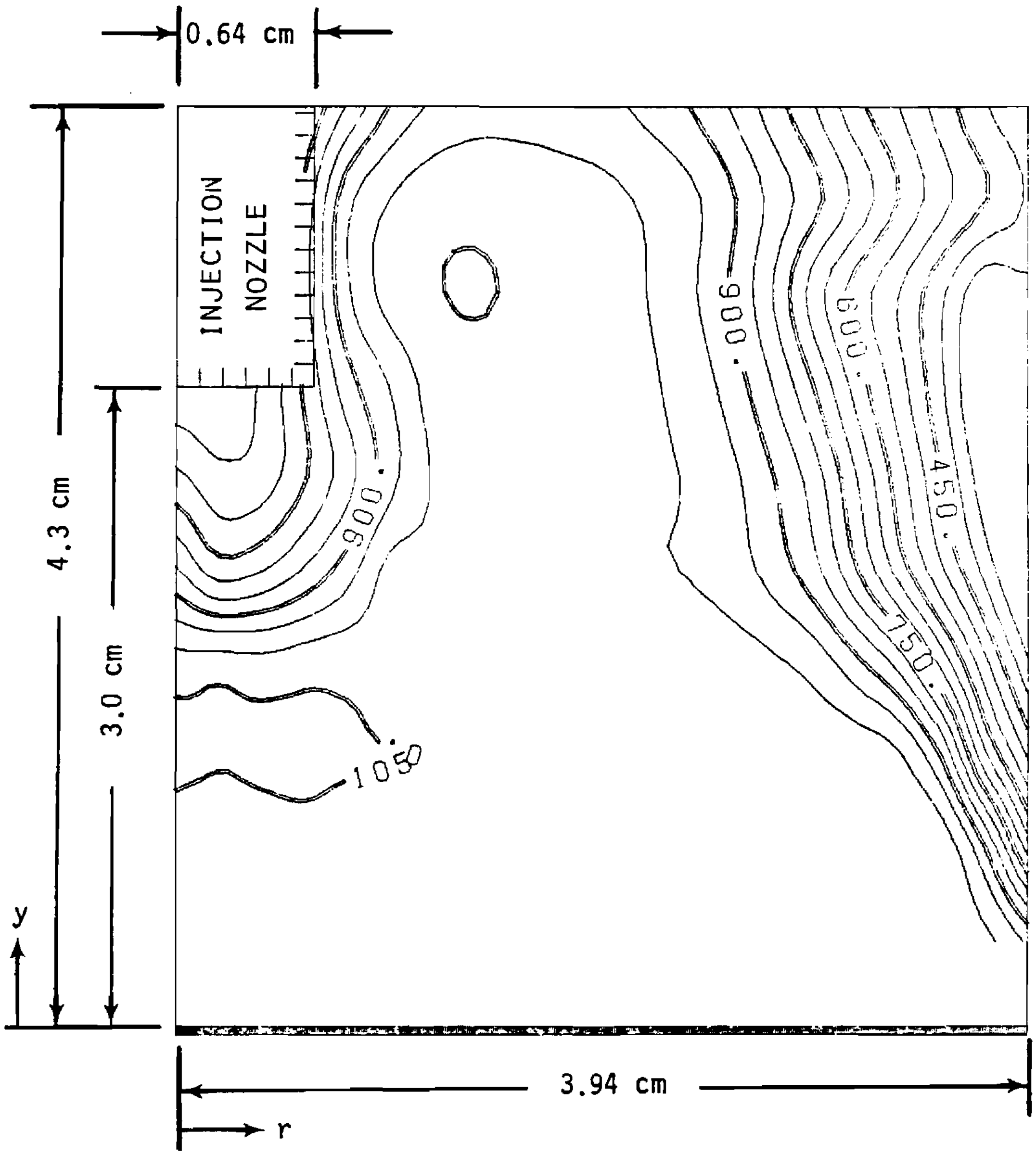


Figure B.28. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.67, $\dot{m}_b$ = 2430 g/h, with Injection of Air, $\dot{m}_{cg}$ = 72.8 g/h, and Lignite Coal Particles 53-74 μm, $\dot{m}_c$ = 15.0 g/h.

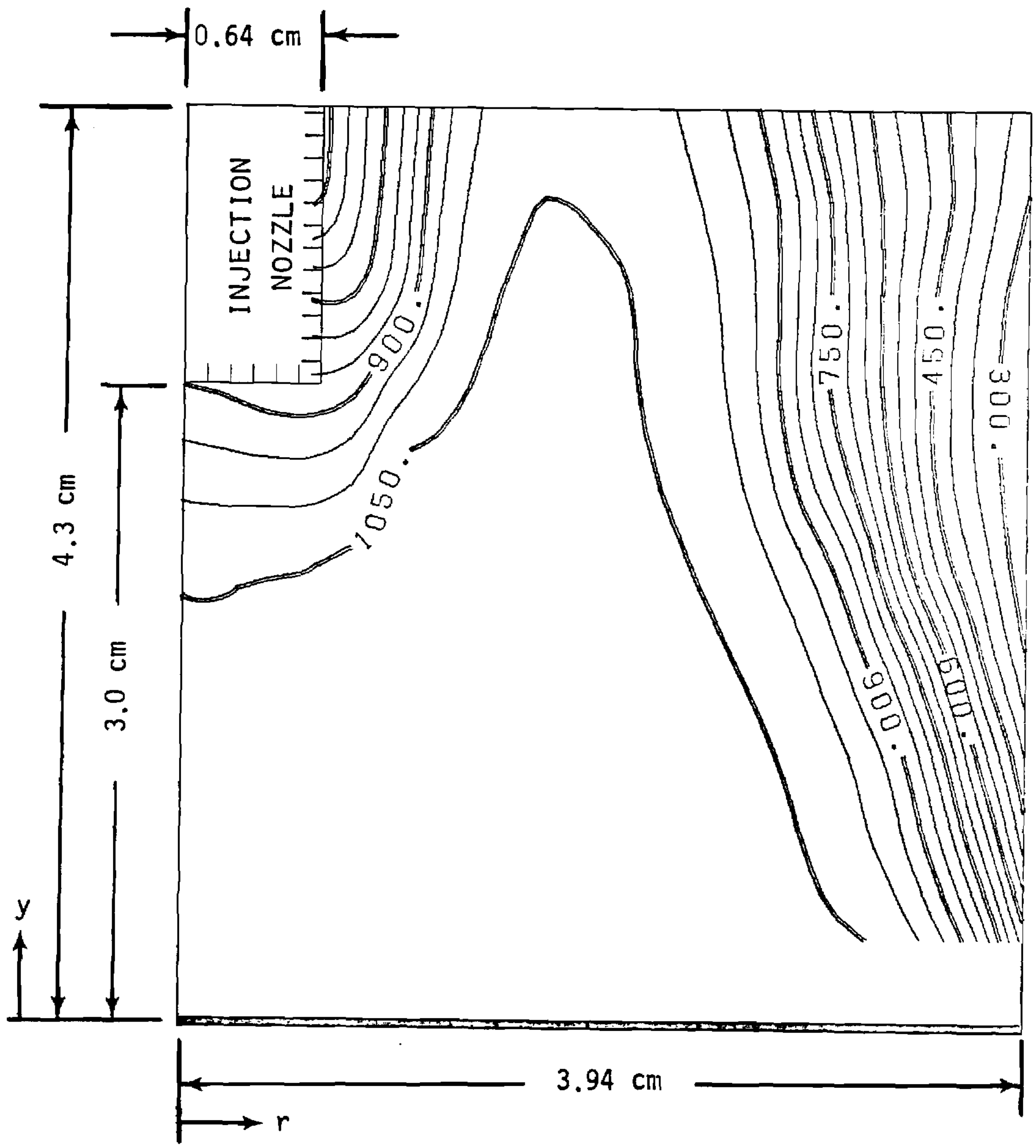


Figure B.29. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2460 g/h, without Injection.

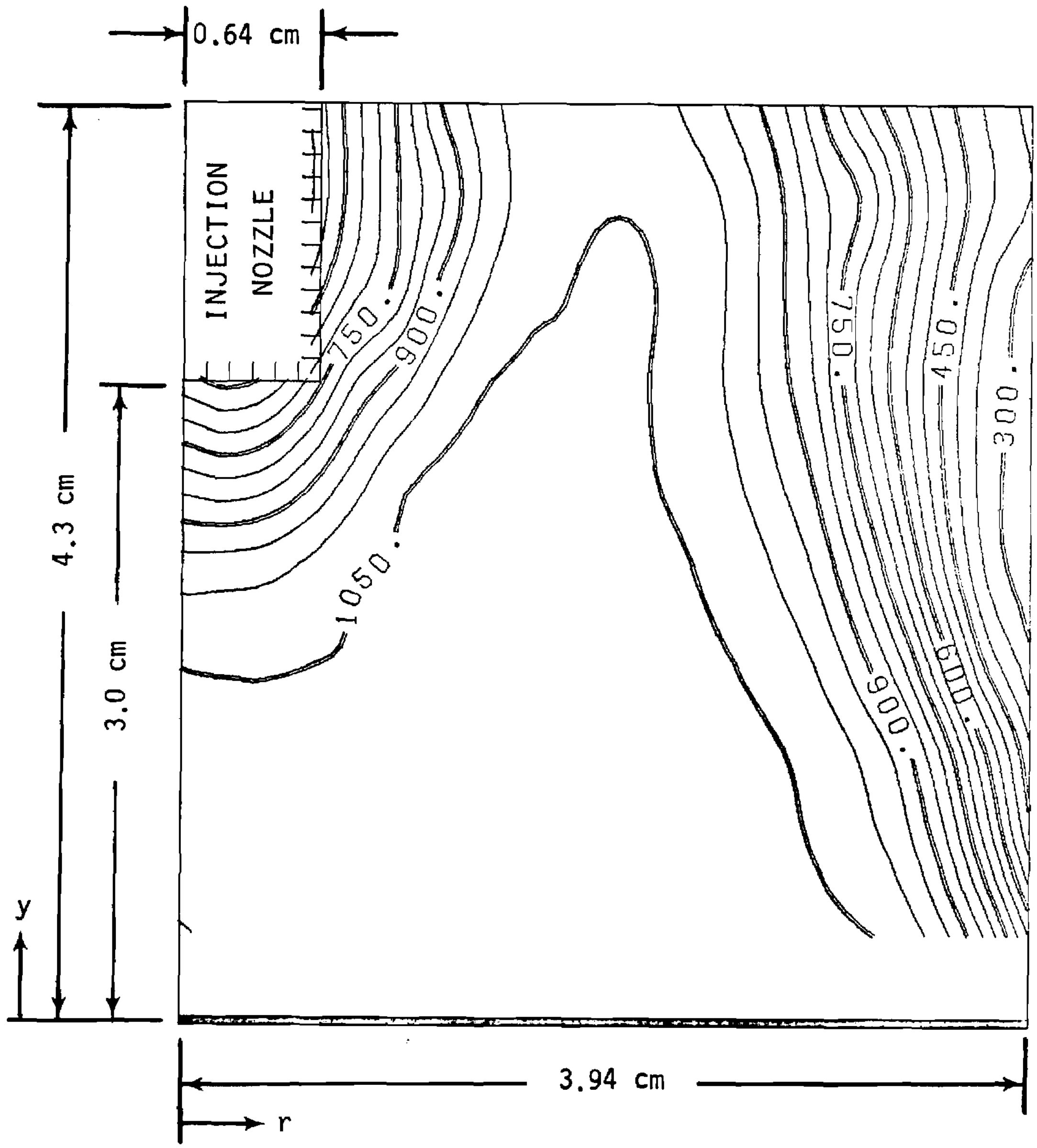


Figure B.30. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2460 g/h, with Injection of Air, $\dot{m}_{cg}$ = 53.7 g/h.

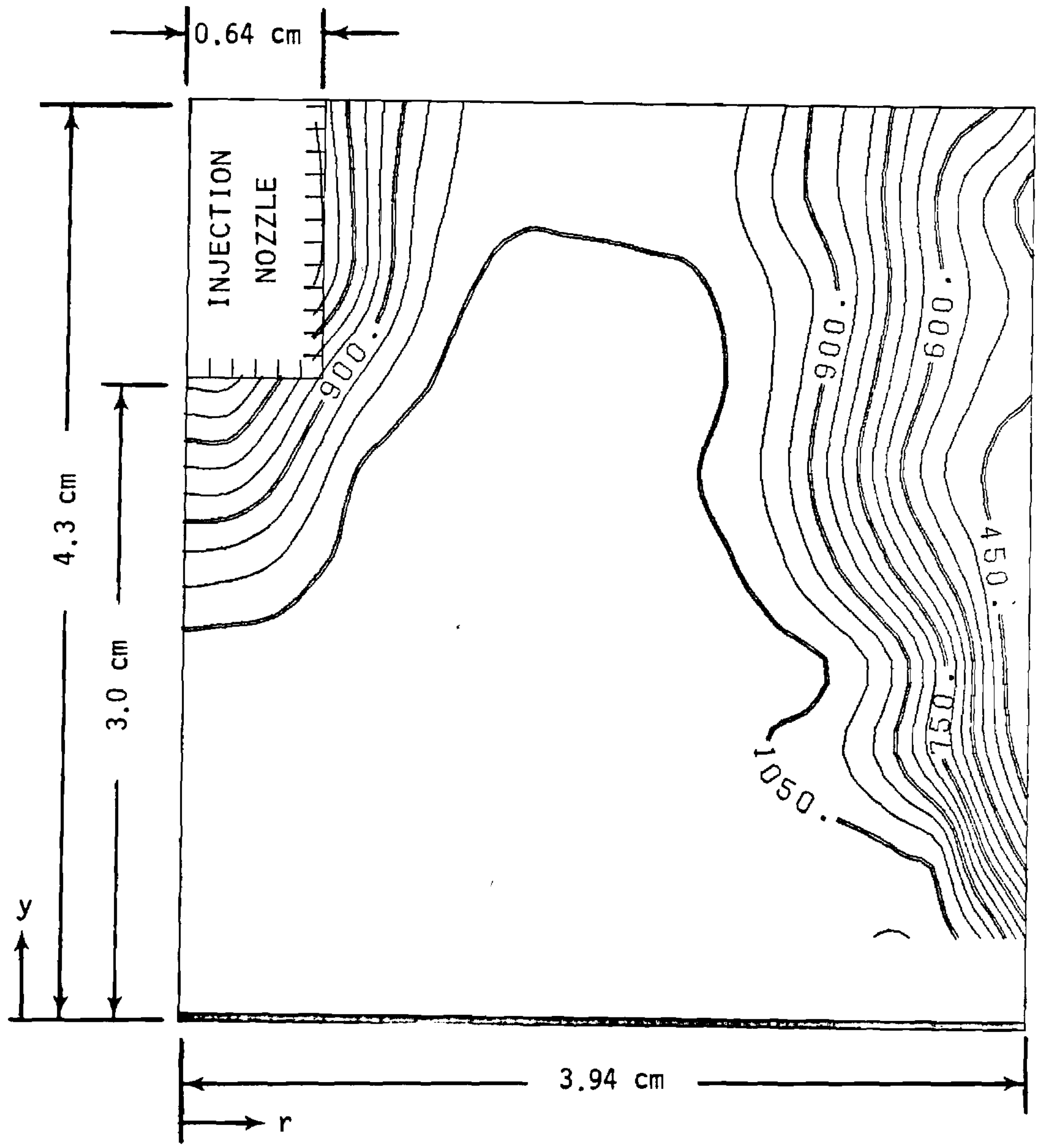


Figure B.31. Isotherms in the Reaction Zone of the Flat Flame Burner, Temperatures in °C, ϕ = 0.86, $\dot{m}_b$ = 2460 g/h, with Injection of Air, $\dot{m}_{cg}$ = 53.7 g/h, and Lignite Coal Particles 53-74 µm, $\dot{m}_c$ = 7.80 g/h.

APPENDIX C

LOWER IGNITION TEMPERATURE AND CONCENTRATION APPARATUS (LITACA)

The Lower Ignition Temperature and Concentration Apparatus (LITACA) has been designed, built and modified to meet the following specifications:

(a) Thermally decompose pyrolyzing materials,
(b) Store the pyrolyzates,
(c) Mix the pyrolyzates with dry air at controlled mass fractions,
(d) Measure the minimum mixture temperature at which self-ignition occurs, and
(e) Afford pyrolyzate sampling for molecular weight determinations.

The six major components of LITACA are:

(i) Pyrolyzate generating furnace,
(ii) Volatile reservoir,
(iii) Pyrolyzate and air metering system,
(iv) Reaction cell,
(v) Temperature recording and ignition detection instrumentation, and
(vi) Pyrolysis timing and power control equipment.

Detailed description of LITACA prior to the current modifications and the operating procedures have been presented in References [22,34, 35]. This appendix describes the apparatus in the form used for the research presented in this report. A schematic diagram of LITACA is given in Figure C.1.

C.1. Pyrolyzate Generating Furnace

The furnace selected to provide high heating rates for the pyrolysis of the samples in the quartz sample tube is an RI Model E4-10-W-A furnace with Quad-Elliptical heating chamber which has four elliptically shaped reflectors that focus radiant energy from tungsten

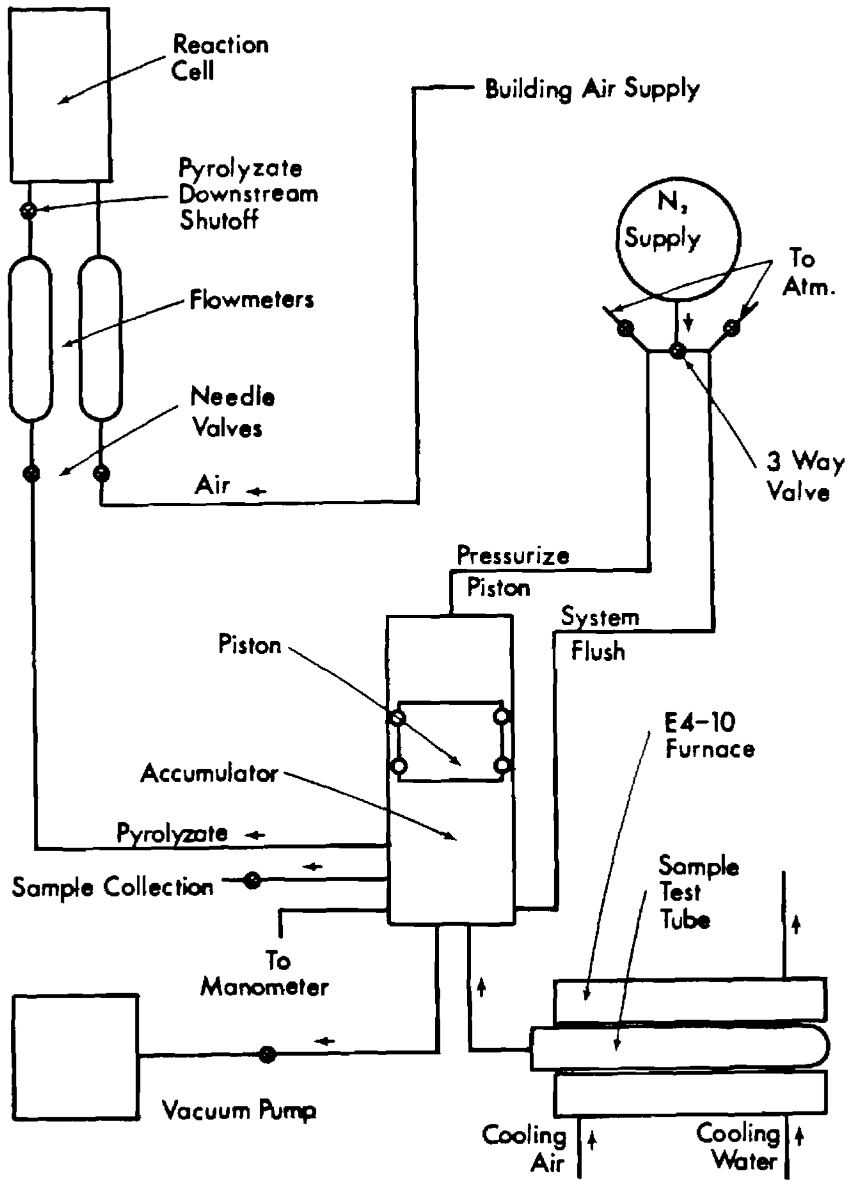


Figure C.1. Lower Ignition Temperature and Concentration Apparatus (LITACA) Schematic.

filament infrared lamps onto the cylindrical quartz sample holder tube. The four infrared lamps are each 1000 watt, type T3/2CL HT, wired in parallel producing a 4 kW at 240 V. The lamps have a 25.4 cm lighted length. Air and water cooling is used with the radiant heater furnace. The furnace is supported in a horizontal position.

The quartz sample test tube used with the furnace is 2.5 cm i.d. and 38.6 cm long. This tube has a flange connection on one end and is closed at the other end. A second quartz sample holder tube has also been manufactured which is 2.5 cm i.d., has a flange connection on both ends of the tube and is 43.2 cm long. Each tube is held against a special adapter flange by a cast iron flange and sealed by a teflon gasket. The adapter flange is supported on the furnace support frame by two steel angle supports and allows free rotation of the test tube in the vertical plane. With this adapter, a stainless steel bellows and a length of stainless steel tubing the quartz sample tube is connected to the bottom supporting flange of the accumulator. Both the stainless steel tubing and the bellows are guard heated. Monitoring thermocouples are used with the guard heaters to insure that proper temperature is maintained.

A stainless steel screen support was manufactured to support the coal particles. This screen support is placed in the center of the quartz sample holder tube and the particles are spread throughout the length of the screen.

C.2. Pyrolyzate Reservoir

The pyrolyzate reservoir, also known as the accumulator, with its accumulator barrel and floating piston serves two functions. During the pyrolysis process the piston in the cylinder of the accumulator expands the volume to collect the generated gases. During the ignition tests the top of the piston is pressurized to drive the accumulated pyrolyzate through a flow meter to the reaction cell. The accumulator maximum capacity is about 1900 cm^3. The accumulator manifold, which is the bottom flange, supports the accumulator barrel and provides ports for access to: (a) the vacuum pump, (b) the gas sampling tap, (c) the pyrolyzate flow meter, (d) the system pressure gage, and (e) the nitrogen supply.

The top flange of the accumulator is tapped with a tube fitting and provides access to the top of the floating piston. The upper end of the piston thus can be either vented to the atmosphere or being pressurized. The top of the piston usually is vented to the atmosphere when it accumulates the generated pyrolysis gases and it is being pressurized with nitrogen when it is used to push the pyrolyzate into the flow metering system through the accumulator manifold.

The accumulator barrel is wrapped with guard heaters. A chromel-alumel thermocouple positioned on the outer surface of the accumulator barrel serves to monitor its wall temperature.

C.3. Pyrolyzate and Air Metering System

The air and pyrolyzate are metered through two Brooks Instrument variable area flow meters before entering a mixing chamber in the reaction cell. The air is metered through an R-2-15-D flow tube with glass and stainless steel floats. The stainless steel float has a maximum range of 830 cm^3/s at s.t.p. of air and the glass 375 cm^3/s at s.t.p. of air.

The pyrolyzate gases are metered through an R-2-15-AAA flow tube with glass and stainless steel floats. The maximum range of these floats is 49 and 147 cm^3/s at s.t.p. of air, respectively. The pyrolyzate flow meter is guard heated.

Both the air and the pyrolyzate flow rates are controlled by needle valves. The pyrolyzate line, in addition, has a shut-off valve downstream of the flow meter.

Air to the air flow meter is supplied from a compressor. It is first taken through a separator, a ceramic filter, a chemical dessicator and a pressure regulator before it is delivered through the flow meter to the reaction cell.

C.4. Reaction Cell

The reaction cell serves to mix the air and pyrolyzates, preheat them and then heat them to their self-ignition temperature. It consists of:

(i) A mixing chamber filled with 3 mm diameter glass beads,
(ii) A 10 mm i.d., 12.8 cm long quartz ignition tube,
(iii) A preignition heater,
(iv) An ignition heater, consisting of two 515 watt cylindrical half-shell heaters, and
(v) Upper and lower guard heaters.

Seven 3 mm o.d. and 2 mm i.d. tubes, 30 mm long form a tube bundle positioned into the ignition tube 3 mm below the top edge of the tube. A schematic view of the reaction cell is shown in Figure C.2.

C.5. Pyrolysis Timing and Power Control

Three power levels were considered necessary for the operation of the radiant heater pyrolyzate generating furnace. First, a preheat power level was found necessary to bring the sample to a temperature of 125-150°C, prior to the initiation of the pyrolysis process, and thus reduce the thermal shock to the components of the furnace and the sample test tube. Next, a higher level of power was needed for the heating of the samples in the sample test tube. Finally, at the completion of the pyrolysis process the furnace had to be maintained at 1250-150°C to prevent condensation in the sample test tube.

Two sets of power control transformers were used to achieve the three level operation of the radiant heater pyrolyzate furnace. The three level operation has been designed to be carried out either manually or automatically. In the automatic control mode, three timers are used to control the sequence of events. A preheat timer is used to provide preheat power in the furnace up to a maximum of two minutes. At the termination of the preheat period the preheat power is switched off and the pyrolysis power supply is switched on. The duration of the heating for the pyrolysis period is controlled by one of two timers. One allows a maximum of 30 seconds for pyrolysis and the second a maximum of 300 seconds. At the conclusion of the pyrolysis period the pyrolysis power supply is turned off and the furnace is switched to postheat using the same power used for the preheating. The postheat

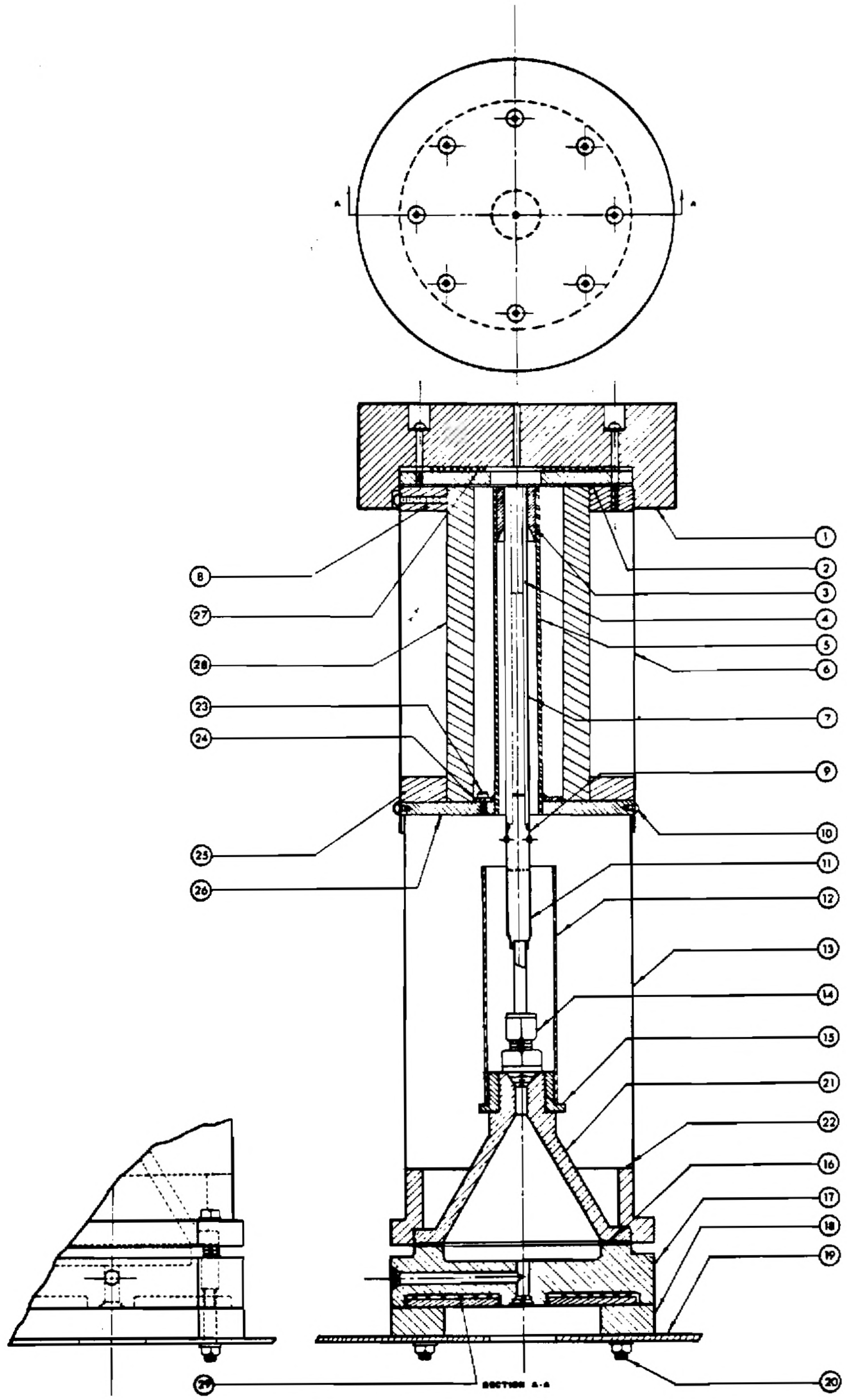


Figure C.2. Cross-Sectional View of Reaction Cell for LITACA.

Key to Figure C.2

Part No.	Description	Material	Req'd
1	Insulation Cap	Asbestos	1
2	Reaction Cell Lid	Transite	1
3	Bushing	Transite	1
4	Tube Bundle	Quartz	1
5	Ignition Tube Shield	Stainless Steel	1
6	Upper Cell Housing	6061-T6 Aluminum	1
7	Ignition Tube	Fused Quartz	1
8	Bushing	Transite	1
9	Graded Seal	Quartz-Pyrex Glass	1
10	6-32UNC Rd Hd Mach Scr	SAE Grade 5	4
11	Seal	Pyrex Glass-Kovar	1
12	Preheater Support	Stainless Steel	1
13	Lower Cell Housing	6061-T6 Aluminum	1
14	1/8NPT-1/4 Male Conn.	316 Stainless Steel	1
15	Bushing	Transite	1
16	Gasket	Teflon	1
17	Mixing Chamber	Chrome Plated Brass	1
18	Spacer	Transite	2
19	Support Shelf	Aluminum	1
20	1/4-20UNC Nut & Bolt	SAE Grade 5	4
21	Flame Arresting Chamber	Chrome Plated Brass	1
22	Bushing	Transite	1
23	6-32UNC Hx Hd Mach Scr	SAE Grade 5	3
24	Flange	Stainless Steel	1
25	Bushing	Transite	1
26	Upper Cell Base	Transite	1
27	Upper Guard Heater	Nichrome Wire	1
28	Ignition Heater	Chrome-Al-Fe Wire	1
29	Lower Guard Heater	Nichrome Wire	1

is not connected to a timer and remains on until the system is reset.

C.6. Guard Heating

All the tubing that carry the pyrolyzates are provided with guard heating. The entire tube guard heating is controlled by an autotransformer. In addition to the tubes, guard heating is provided for the accumulator, the furnace tube and the upper and lower ends of the reaction cell. Each one of these guard heaters is provided with a separate control.

C.7. Temperature Recording and Ignition Detection Instrumentation

Two major functions are performed by the temperature measuring instrumentation. The first and primary function is the gas temperature measurement and ignition detection in the quartz tube of the reaction cell. The second and auxiliary function is the monitoring of temperatures at various stations in the system to assure proper execution of the pyrolysis process and the self-ignition tests.

The ignition detecting thermocouples measure the gas temperature down the centerline of the quartz ignition tube. The thermocouples are chromel-alumel of 0.25 mm diameter wire. There are three thermocouples in the array and they are placed 3.5 cm and 7.5 cm below the top edge of the quartz ignition tube. The thermocouple located at 5.5 cm is located at or near the point of maximum temperature in the ignition tube. This and the thermocouple at 7.5 cm are the most sensitive to ignition, since during most tests flames propagated downward. A fourth thermocouple was placed outside the ignition tube and in line with the inside thermocouple at the 5.5 cm location. The temperature measured by this thermocouple is used as a reference to the three inside thermocouples to establish temperature differences in the ignition detection measurements.

The thermocouple lead wires pass through ceramic insulating tubes of appropriate length which in turn are inserted through holes in the insulating cap of the upper guard heater. The ceramic insulators are guided and kept separated by the small quartz tube bundle at the top of the ignition tube. The thermocouple leads are connected to Omega MCJ-K electronic cold junction compensators and in turn to electronic equipment which condition and record their signal, including signals indicating ignition.

The flame temperature of the pyrolyzate-air mixtures may be as low as a few degrees above the self-ignition temperatures. The detection of small thermal excursions in the ignition tube, therefore, requires a method to increase the sensitivity of the ignition detection instrumentation. This is accomplished by separating the millivolt output of the thermocouple into the integral part and the fractional part. The fraction of one millivolt is then amplified 100 times and recorded on a strip chart recorder. The integer part of the signal is recorded on the chart by hand.

Three separate groups of instruments are used to achieve the signal conditioning of the thermocouples in the quartz ignition tube. A schematic view of the thermocouples in the reaction cell and the associated ignition detection instrumentation is shown in Figure C.3.

C.8. Instrumentation for Molal Mass Determination

The instrumentation used in determining apparent molecular weights of the pyrolyzate gases consists of the following components:

(i) Two 7.6 cm single-valve glass balloons,
(ii) A vacuum pump,
(iii) A McLeod vacuum gage,
(iv) A Model H51 Mettler balance, and
(v) An oven.

A new balloon used to collect a sample of the pyrolyzate gas for apparent molal mass determination, was modified and outfitted with a vacuum petcock. The baloons were used to collect a known volume of the sample pyrolyzate gas from the accumulator barrel. The vacuum pump was used to evacuate each balloon and remove residual gases before the tare weight measurements. Tare weight and gross weight measurements were made with the Mettler balance which has a resolution of 10^{-5} g. The

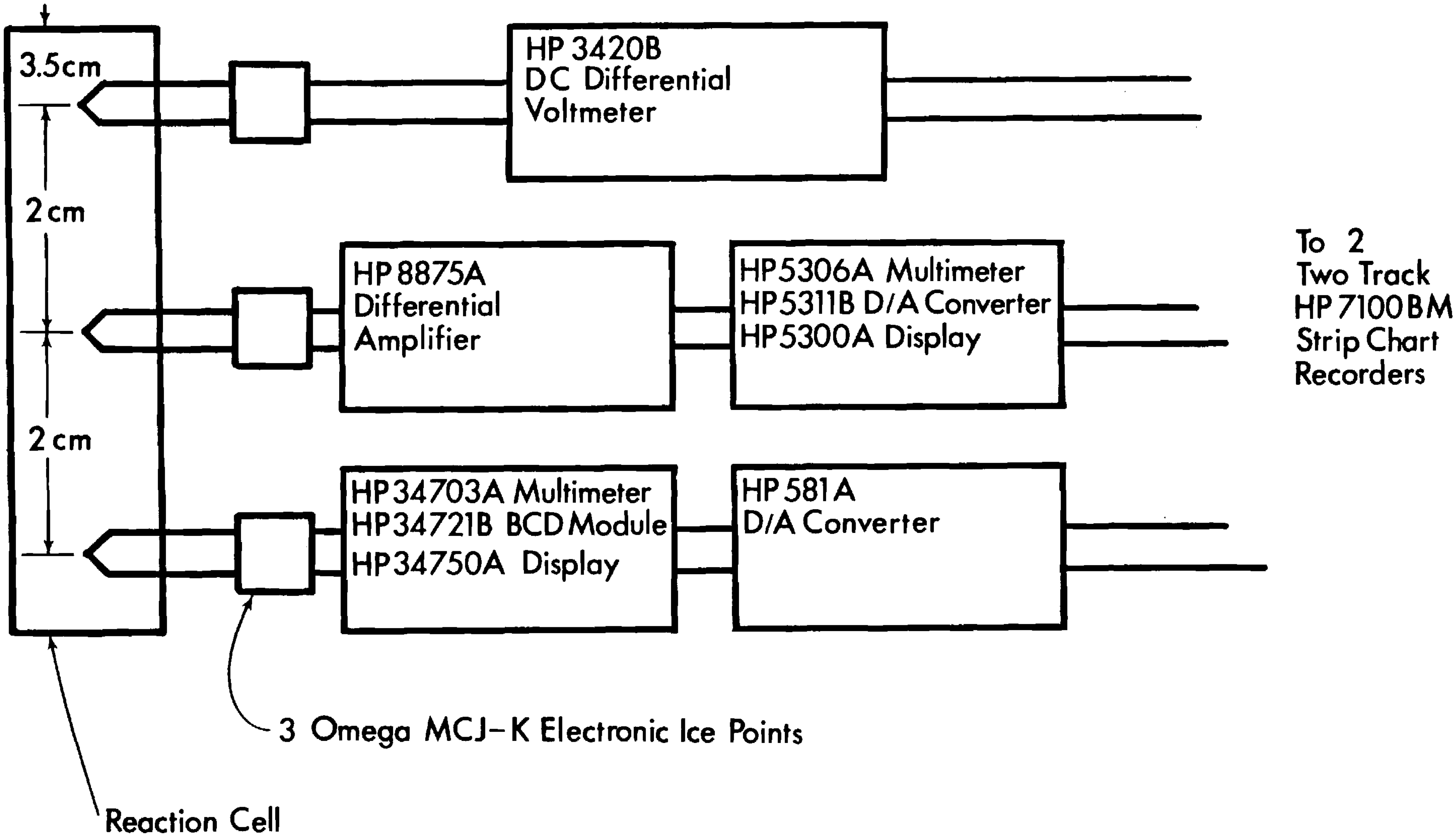


Figure C.3. Schematic View of LITACA Ignition Detection Instrumentation.

over was used to provide a known reference temperature for the sampled pyrolyzate gases to come to equilibrium.

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